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IEEE Recommended Practice for the Application of Power Distribution Apparatus in Industrial and Commercial Power Systems

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IEEE Recommended Practice for the Application of Power Distribution Apparatus in Industrial and Commercial Power Systems

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Abstract: The selection and application of power distribution apparatus used in industrial and commercial power systems are covered in this recommended practice. It is likely to be of greatest value to the power-oriented engineer with limited experience with this equipment. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

Keywords: apparatus, busway, cable systems, circuit breakers, conductors, fuses, IEEE 3001.5™, panelboards, separable insulated connectors, switchboards, switches, switchgear, transformers

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Introduction

This introduction is not part of IEEE Std 3001.5™-2013, IEEE Recommended Practice for the Application of Power Distribution Apparatus in Industrial and Commercial Power Systems.

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This recommended practice was developed by the Technical Books Coordinating Committee of the Industrial and Commercial Power Systems Department of the Industry Applications Society as part of a project to repackage the popular IEEE Color Books®. The goal of this project is to speed up the revision process, eliminate duplicate material, and facilitate use of modern publishing and distribution technologies.

When this project is completed, the technical material in the thirteen IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

— Power Systems Design (3001 series)

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— Power Systems Reliability (3006 series)

— Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

The material in this recommended practice largely comes from Chapter 10, Chapter 12, and Chapter 13 of IEEE Std 141™ (*IEEE Red Book™*), Chapter 5 of IEEE Std 241™ (*IEEE Gray Book™*), and Chapter 4 of IEEE Std 1100™ (*IEEE Emerald Book™*).

IEEE Std 3001.5™

This publication provides a recommended practice for the electrical design of commercial and industrial facilities. It is likely to be of greatest value to the power-oriented engineer with limited commercial or industrial plant experience. It can also be an aid to all engineers responsible for the electrical design of commercial and industrial facilities. However, it is not intended as a replacement for the many excellent engineering texts and handbooks commonly in use, nor is it detailed enough to be a design manual. It should be considered a guide and general reference on electrical design for commercial and industrial facilities.

Tables, charts, and other information that have been extracted from codes, standards, and other technical literature are included in this publication. Their inclusion is for illustrative purposes; where technical accuracy is important, the latest version of the referenced document should be consulted to assure use of complete, up-to-date, and accurate information.

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1. Overview

1.1 Scope

This recommended practice covers the selection and application of power distribution apparatus used in industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience with this equipment. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

Accredited Standards Committee C2-2007, National Electrical Safety Code® (NESC®).[1]

AEIC CS8-07 (Edition 3), Specifications for Extruded Dielectric Shielded Power Cables Rated 5 kV Through 69 kV.[2]

ANSI C57.12.21-1992, American National Standard Requirements for Pad-Mounted, Compartmental-Type Self-Cooled, Single-Phase Distribution Transformers With High Voltage Bushings; High-Voltage, 34500 GRYD/19920 Volts and Below; Low-Voltage, 240/120 Volts; 167 kVA and Smaller.

ANSI C57.12.22-1993 (Reaff 1998), American National Standard for Transformers—Pad-Mounted, Compartmental-Type, Self-Cooled Three-Phase Distribution Transformers With High-Voltage Bushings, 2500 kVA and Smaller: High Voltage, 34 500 Grd Y/19 920 Volts and Below; Low Voltage, 480 Volts and Below.

ANSI C57.12.25-1990, American National Standard for Transformers—Pad-Mounted, Compartmental-Type, Self-Cooled, Single-Phase Distribution Transformers With Separable Insulated High-Voltage Connectors; High Voltage, 34 500 Grdy/19 920 Volts and Below; Low Voltage, 240/120 Volts; 167 kVa and Smaller Requirements.

ANSI C57.12.55-1987 (Reaff 1998), American National Standard for Transformers—Used in Unit Installations, Including Unit Substations-Conformance Standard.

ICEA P-32-382 (2007), Short-Circuit Characteristics of Insulated Cable.[3]

ICEA P-45-482 (2007), Short-Circuit Performance of Metallic Shields and Sheaths of Insulated Cables.

IEEE Std 48™-2009, IEEE Standard for Test Procedures and Requirements for Alternating-Current Cable Terminations Used on Shielded Cables Having Laminated Insulation Rated 2.5 kV through 765 kV or Extruded Insulation Rated 2.5 kV through 500 kV.[4]

IEEE Std 141™-1993, Recommended Practice for Electric Power Distribution in Industrial Plants (*IEEE Red Book™*).

IEEE Std 142™-2007, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (*IEEE Green Book™*).

IEEE Std 242™-2001, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff Book™*).

IEEE Std 386™-2006, IEEE Standard for Separable Insulated Connectors for Power Distribution Systems Above 600 V.

IEEE Std 400™-2012, IEEE Guide For Field Testing And Evaluation Of The Insulation Of Shielded Power Cables Systems Rated 5 kV And Above.

IEEE Std 446™-1995, IEEE Recommended Practice for Emergency and Standby Systems for Industrial and Commercial Applications.

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[1] The NESC® is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).

[2] AEIC publications are available from the Association of Edison Illuminating Companies, 600 N. 18th Street, P. O. Box 2641, Birmingham, AL 35291-0992, USA (http://www.aeic.org/). AEIC publications are also available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112-5704, USA (http://global.ihs.com/).

[3] ICEA publications are available from the Insulated Cable Engineers Association, ICEA P.O. Box 1568 Carrollton, GA 30112, USA (http://www.icea.net/).

[4] IEEE publications are available from The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).

IEEE Std 519™-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

IEEE Std 739™-1995, IEEE Recommended Practice for Energy Conservation and Cost-Effective Planning in Industrial Facilities (*IEEE Bronze Book*™).

IEEE Std 1215™-2001, IEEE Guide for the Application of Separable Insulated Connectors.

IEEE Std C37.010™-1999 (Reaff 2005), IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.011™-2011, IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers.

IEEE Std C37.04™-1999 (Reaff 2006), IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers.

IEEE Std C37.06™-2009, IEEE Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities for Voltages Above 1000 V.

IEEE Std C37.13™-2008, IEEE Standard for Low-Voltage AC Power Circuit Breakers Used in Enclosures.

IEEE Std C37.16™-2009, IEEE Standard for Preferred Ratings, Related Requirements, and Application Recommendations for Low-Voltage AC (635 V and below) and DC (3200 V and below) Power Circuit Breakers.

IEEE Std C37.23™-2003, IEEE Standard for Metal-Enclosed Bus.

IEEE Std C37.20.1™-2002 (Reaff 2007), IEEE Standard for Metal-Enclosed Low-Voltage Power Circuit Breaker Switchgear.

IEEE Std C37.20.2™-1999, IEEE Standard for Metal-Clad Switchgear.

IEEE Std C37.20.3™-2001 (Reaff 2006), IEEE Standard for Metal-Enclosed Interrupter Switch-gear.

IEEE Std C37.20.7™-2007, IEEE Guide for Testing Metal-Enclosed Switchgear Rated up to 38 kV for Internal Arcing Faults.

IEEE Std C37.24™-2003, IEEE Guide for Evaluating the Effect of Solar Radiation on Outdoor Metal-Enclosed Switchgear.

IEEE Std C37.100™-1992 (Reaff 2001), IEEE Standard Definitions for Power Switchgear.

IEEE Std C57.12.00™-2010, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.01™-2005, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers, Including Those with Solid Cast and/or Resin-Encapsulated Windings.

IEEE Std C57.12.10™-2010, IEEE Standard Requirements for Liquid-Immersed Power Transformers.

IEEE Std C57.12.40™-2011, IEEE Standard Requirements for Secondary Network Transformers, Subway and Vault Types (Liquid Immersed).

IEEE Std C57.12.51™-2008, IEEE Standard for Ventilated Dry-Type Power Transformers, 501 kVA and Larger, Three-Phase, with High-Voltage 601 V to 34 500 V; Low-Voltage 208Y/120 V to 4160 V—General Requirements.

IEEE Std C57.12.80™-2010, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90™-2010, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.91™-2011, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

IEEE Std C57.96™-1999 (Reaff 2004), IEEE Guide for Loading Dry-Type Distribution and Power Transformers.

IEEE Std C57.110™-2008, IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents.

NEMA BU l.1-2010, General Instructions for Proper Handling, Installation, Operation, and Maintenance of Busway Rated 600 Volts or Less. [5]

NEMA FB 11-2000, Plugs, Receptacles, and Connectors of the Pin and Sleeve Type for Hazardous Locations.

NEMA PB 2-2011, Deadfront Distribution Switchboards.

NEMA PB 2.1-2007, General Instructions for Proper Handling, Installation, Operation and Maintenance of Deadfront Distribution Switchboards Rated 600 V or Less.

NEMA TP 1-2002, Guide for Determining Energy Efficiency for Distribution Transformers.

NEMA TR 1-1993 (Reaff 2000), Transformers, Regulators, and Reactors.

NEMA WC 70-2009, Power Cables Rated 2000 Volts or Less for the Distribution of Electrical Energy.

NEMA WC 71-1999, Standard for Nonshielded Cables Rated 2001-5000 Volts for use in the Distribution of Electric Energy.

NEMA WC 74-2006, 5-46KV Shielded Power Cable for Use in the Transmission and Distribution of Electric Energy.

NFPA 70®, National Electrical Code®. [6]

NFPA 70E®-2012, Standard for Electrical Safety in the Workplace.

UL 67, 12th Edition, Rev. 2010, Standard for Panelboards. [7]

UL 98, 13th Edition, Rev. 2012, Enclosed and Dead-Front Switches.

UL 486a-486b, 1st Edition, Rev. 2011, Wire Connectors.

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[5] NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA (http://global.ihs.com/).
[6] NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (http://www.nfpa.org/).
[7] UL standards are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (http://www.global.ihs.com/).

UL 489, 11th Edition, Rev. 2011, Molded-Case Circuit Breakers, Molded-Case Switches, and Circuit-Breaker Enclosures.

UL 857, 13th Edition, Rev. 2011, Busways.

UL 891, 11th Edition, Rev. 2005, Switchboards.

UL 977, 5th Edition, Rev. 2012, Standard for Fused Power-Circuit Devices.

UL 1008, 6th Edition, Rev. 2012, Standard for Transfer Switch Equipment.

UL 1066, 4th Edition, Rev. 2012, Standard for Low-Voltage AC and DC Power Circuit Breakers Used in Enclosures.

UL 1558, 4th Edition, Rev. 2010, Standard for Metal-Enclosed Low-Voltage Power Circuit Breaker Switchgear.

UL 1561, 4th Edition, Rev. 2011, Standard for Dry-Type General Purpose and Power Transformers.

UL 1562, 3rd Edition, Rev. 2001, Standard for Transformers, Distribution, Dry-Type Over 600 Volts.

3. Introduction

This recommended practice provides information on the requirements for, and application of, major apparatus utilized in industrial and commercial electric distribution systems. More detailed information on this type of apparatus is available from the American National Standards Institute (ANSI), the National Electrical Manufacturers Association (NEMA), and nationally recognized testing laboratories (NRTLs), such as Underwriters Laboratories, Inc., (UL) or Factory Mutual (FM), as well as from manufacturers' publications.

The engineer should make basic decisions in the choice of equipment for a particular electric system. The decision-making process should entail all those factors involved in designing and maintaining an electric power system, such as safety, protection, continuity of service, reliability, security, protective coordination, initial installed cost, procurement time to meet the schedule, flexibility, staffing, and cost for operating and maintenance. Energy cost, conservation, and environmental protection should be considered in initial plant design and equipment. For information related to energy cost and conservation, refer to IEEE Std 141™-1993 (*IEEE Red Book*™) Chapter 14.

The engineer should anticipate how operating personnel will need to interface with energized equipment and the work that may be required to be performed in proximity to the equipment while energized. Such work must be conducted in accordance with NFPA 70E®, whose purpose is to "provide a practical safe working area for employees relative to the hazards arising from the use of electricity." Procedures for risk assessment and the determination of required personal protective equipment (PPE) for specific tasks are provided in this standard. The PPE requirements can be affected significantly by the prospective arc flash available within the electrical equipment. Equipment choices may be available to the designer to reduce the risk of arc flash and/or reduce its severity to create a safer work environment. NFPA 70E® Annex O addresses safety-related design requirements. For information regarding the determination of arcing currents and arc flash energy for the purpose of selecting PPE, refer to IEEE Std 1584™-2002.

3.1 Equipment installation

Electric equipment should be installed in a manner that is safe yet readily accessible to qualified personnel. Sufficient working space should be provided and maintained about all electric apparatus to permit ready

and safe operation and maintenance of such equipment. Minimum working clearances around electrical equipment as required by the National Electrical Code® (NEC®) (NFPA 70®) shall be considered for design and installation.

Installations in industrial plants require that adequate aisles, hatchways, wall openings, etc., be provided for easy removal and replacement of all electric equipment. For medium-voltage switching equipment, extreme care should be exercised in setting, grouting, aligning, and leveling the floor channels in order to prevent stressing insulators and bus structures and to provide for easy insertion and removal of the apparatus. Floor area in front of switchgear should be level or have only a moderate slope away from the equipment for adequate drainage.

Special attention should be given to the floor under and in front of any equipment that is required to roll in and out of the enclosure. More detailed installation procedures are given in NEMA PB 2.1-2007. If equipment is to be stored or installed in locations where internal condensation may occur, suitable internal heating should be provided (NEMA PB 2.1- 2007, Section 3).

Article 450 of the NEC outlines the installation requirements for transformers of various types. In some industrial plants, the unit substation transformer is located outside a pressure-ventilated switchgear room with a secondary throat connection for buswork through the wall. This pressure-ventilated switchgear room may also house motor-control centers, panelboards, and other electrical and electronic equipment in addition to the switchgear. This particular type of design would be used for the following reasons:

a) Protection of electric equipment from the accumulation of dirt, dust, and other foreign material.

b) Use of less expensive and more readily maintainable general-purpose electric equipment enclosures, where appropriate.

c) Prevention of access by unauthorized people.

3.2 Maintenance, testing, and safety

Maintenance, testing, and safety of an operating plant must be considered primary factors in the design of any electrical system.

An effective preventive maintenance program should sustain production at required levels, protect valuable investment, and reduce down time and maintenance costs. Planned maintenance should include a series of tasks to be performed on each unit of equipment in order to detect areas of potential failure and to provide a warning to plan for necessary repairs or replacement. The tasks should be performed either on a regularly scheduled basis or on the basis of time in service, cycles of operation, or having interrupted fault current. Record keeping is an essential part of the planned maintenance program. Inherent with any maintenance program is the testing of electric equipment and appropriate safety precautions for personnel and equipment. IEEE Std 3007.2™-2010 [B43] discusses general methods of testing protective equipment, such as circuit breakers, relays, etc. Specific procedures and testing procedures for other equipment are found in appropriate standards of the IEEE, the American National Standards Institute (ANSI), National Fire Protection Association (NFPA®), National Electrical Manufacturers Association (NEMA), and the National Electrical Testing Association (NETA), as well as in manufacturers' literature.

3.3 Heat losses

The heat generated by power losses in electric equipment, particularly transformers, motors, rectifiers, and motor control centers, should be considered in the initial design of a project. An estimate of the power losses that show up as heat should be developed and added to the cooling requirements of the building. Table 1 lists the range of losses in electric equipment. Heat losses for specific equipment should be obtained from the manufacturer.

Exhausting air from the equipment location and allowing cooler (even if filtered) air to enter may cause internal condensation and possibly create a hazardous atmosphere in the building. Alternate methods include air conditioning, ventilation with dehumidification, higher efficiency equipment, or locating the major heat-producing items outdoors. The amount of cooling air should be kept at the required minimum by use of the thermally controlled equipment.

Table 1—Range of losses in power system equipment

Component	Percent energy loss[a] (full load)
Outdoor circuit breakers (15 V to 230 kV)	0.002 to 0.015
Generators	0.09 to 3.50
Medium-voltage switchgear (5 V and 15 kV)	0.005 to 0.02
Current-limiting reactors (600 V-15 kV)	0.09 to 0.30
Transformers	0.40 to 1.90
Load break switches	0.003 to 0.025
Medium-voltage starters	0.02 to 0.15
Busway (480 V and below)	0.05 to 0.50
Low-voltage switchgear	0.13 to 0.34
Motor-control centers	0.01 to 0.40
Cable	1.00 to 4.00
Motors 1 hp to 10 hp 10 hp to 200 hp 200 hp to 1500 hp 1500 hp and up	 14.00 to 35.00 6.00 to 12.00 4.00 to 7.00 2.30 to 4.50
Rectifiers (large)	3.00 to 9.00
Static variable speed drivers	6.00 to 15.00
Capacitors (watts loss/var)	0.50 to 2.00
Lighting (lumens/watts)	8.00 to 9.00
NOTE—Data on capacitors and lighting systems (fixtures and controls) should be obtained from manufacturers and considered in calculating power losses. [a]Percent energy loss is simply a ratio of power consumed internally in equipment to the total energy passed through it.	

Source: Reprinted from H. N. Hickock, "Electrical Energy Losses in Power Systems," *IEEE Transactions on Industry Applications*, vol. JA-14, no. 5, Sept./Oct. 1978.

4. Switching apparatus for power circuits

4.1 Classifications

Switching apparatus can be defined as a device for opening and closing, or for changing the connections of a circuit. The general classification of switching apparatus as used in this chapter includes switches, fuses, circuit breakers, and service protectors.

4.2 Switches

The types of switches normally used for power circuits include the following:

a) Isolating

b) Load interrupter

c) Safety switches for 600 V and lower power applications, including bolted-pressure switches and high-pressure contact switches and power protectors

d) Transfer switches for load transfer, including emergency and standby switching

4.2.1 Isolating switches

An isolating switch is used to provide a visible disconnect and frequently has no interrupting current rating, in which case it may be referred to as a "no-load switch." It should be operated only after the circuit has been opened by other means. Interlocking is generally provided to prevent operation when the switch is carrying current. Latches may be required to prevent the switch from being opened by magnetic forces under heavy fault currents.

4.2.2 Load interrupting switches

For services above 600 V, a load interrupter or load-break switch, generally associated with unit substations supplied from the primary distribution system, is a switch combining the functions of a disconnecting switch and a load interrupter for interrupting, at rated voltage, currents not exceeding the continuous-current rating of the switch. Load-break switches are of the air, fluid-immersed, or vacuum type. The interrupter switch is usually manually operated and has a quick-make, quick-break mechanism that functions independently of the speed-of-handle operation. Such switches usually have a fault-making current rating to provide additional capabilities in the event of closing-in on a faulted circuit.

With a fused load-break switch combination, fast fault clearing and circuit isolation can be provided. This application, if properly coordinated to protect the transformer and to interrupt transformer magnetizing currents and load currents within the switch rating, may be more economical than a circuit breaker.

Rollout fuse-switch assemblies, produced by several manufacturers, have advantages such as replacing of fuses without the necessity of de-energizing the primary circuit, the ability to fuse on the line side of the switch, and complete accessibility to mechanical parts for checkout and maintenance.

It may be desirable from a safety standpoint in the case of a transformer application to interlock the operation of an interrupter switch with the secondary circuit breaker to minimize the chance of operating the interrupter switch at a time when the current exceeds the interrupting rating of the switch. Load interrupter switches having isolating blades are also available with vacuum interrupters and electronic fuses and may be actuated by ground-fault protective relaying, or phase failure protective relaying and fuses.

4.2.3 Switches for 600 V and below

The application of fused safety switches is described in the NEC and requires a continuous-current rating of at least 115% of the full-load current rating of the motor.

For services of 600 V and below, safety circuit breakers and switches are commonly used. Safety switches are enclosed and may be fused or unfused. This type of switching device is operable by means of a handle from outside the enclosure and is interlocked so that the enclosure cannot be opened unless the switch is open or the interlock defeater is operated. Many safety switches have quick-make and quick-break features.

A safety switch for motors is rated in horsepower, and voltage and is capable of interrupting the maximum operating current of a motor of the same horsepower at rated voltage. The maximum operating current of the motor is the locked-rotor current and is recognized by the NEC as six times full-load motor current.

Safety switches with current-limiting fuses can be applied to circuits with up to 200 000 A rms symmetrical fault current if the switch-fuse combination has been tested by an NRTL. Switches are labeled either by an NRTL or the manufacturer to indicate the particular switch-fuse combination that must be used to obtain the specified rating. It should never be assumed that interchanging fuses of a different class, even if they have the same rating, will result in safe switch application.

The bolted-pressure switch consists of movable blades and stationary contacts with arcing contacts and a mechanism for applying bolted pressure to both the hinge and jaw contacts in a manner similar to a bolted bus joint. Thus, a high degree of short-circuit withstandability is accomplished. The bolted-pressure switch can be applied at 100% of its continuous current rating. Some mechanisms have a spring that is compressed by the operating handle and released at the end of the operating stroke to provide quick-make, quick-break switching action.

The electrical-trip bolted-pressure switch is basically the same as the manually operated bolted-pressure switch, except that a stored-energy latch mechanism and a solenoid trip release are added to provide automatic electrical opening. All the other features normally required on low-voltage main and feeder circuits rated 600 A and above are available. These switches also can be designed for use with ground-fault protection equipment that may be required by the NEC. Bolted-pressure switches have a contact interrupting rating of 12 times the continuous current rating. These switches are available in ratings of 600 A, 800 A, 1200 A, 1600 A, 2000 A, 2500 A, 3000 A, 4000 A, 5000 A, and 6000 A, 600 Vac, and are suitable for use on circuits having available fault currents of up to 200 000 A rms symmetrical, when applied in combination with Class L current-limiting fuses.

A switch with a shunt-trip device and with a stored energy release (opening) mechanism is triggered by a voltage signal derived from the main circuit or from an independent source. A shunt-trip is used on a switch to provide the tripping required for ground-fault protection or other requirements, such as an application where it is desirable to open all three phases when one or two fuses open.

A second specialized type of safety switch is the high-pressure contact switch, which has an over-center toggle mechanism that provides stored energy for quick-make, quick-break operation. Multiple spring-loaded high-pressure current-carrying contact arms and an arcing contact arm provide high current-carrying capability without sacrificing high interrupting fault performance.

These switches can be applied at 100% of their continuous current rating and can interrupt on a make-and-break basis a minimum of 12 times their nameplate continuous-current rating without fuse assistance at 600 Vac. Therefore, complete switch and current-limiting fuse (Class L) coordination is achieved for all levels of fault current to a maximum of 200 000 A rms symmetrical at 600 Vac. These switches are available in continuous current ratings of 800 A, 1200 A, 1600 A, 2000 A, 2500 A, 3000 A, and 4000 A at 600 Vac maximum and are suitable for use at all short-circuit currents up to 200 000 A rms symmetrical when used with Class L current-limiting fuses.

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The high-pressure contact switch can be equipped for manual tripping when ground-fault or remote tripping is not required. When equipped with a shunt trip, the switch can be remotely tripped, and/or have remote ground fault function applied; external control power is required. When integral ground fault function is applied, it is self-powered; however, the test function does require an external power source. Single-phase protection is available, which will trip the switch when a fuse or fuses open or the switch is closed with an open fuse or fuses.

4.3 Transfer switches

Automatic transfer switches (ATS) of double-throw construction are primarily used for emergency and standby power generation systems rated 600 V and less. These transfer switches do not normally incorporate overcurrent protection and are designed and applied in accordance with UL 1008 and the NEC, particularly Articles 230, 517, 700, 701, 702, and 708. For reliability, most automatic transfer switches rated above 100 A are mechanically held and are electrically operated from the power source to which the load is to be transferred.

Automatic transfer switches are available in the following forms:

1) Automatic or manual transfer switches available in ratings to 4000 A in low-voltage class, and to 1200 A in medium-voltage class. These switches may be fusible or nonfusible.

2) Automatic power circuit breakers consisting of two or more power circuit breakers, which are mechanically or electrically interlocked, or both, rated 600 A to 3000 A, in both low- and medium-voltage classes. The breakers can be provided as a stand-alone automatic transfer switch, or the incoming main breakers on switchgear can be provided with electrical operators and used for transfer applications. Transfer control of circuit breakers can be handled by discrete control relays, a programmable logic controller, or a protective relay that has control logic capability. There are two major advantages to using circuit breakers. The circuit breakers provide an interrupting rating (as opposed to a withstand rating for a transfer switch, which is dependent on an upstream overcurrent device) and the circuit breakers also provide overcurrent protection.

3) Manually or electrically operated bolted pressure switches (600 V), which are fusible or nonfusible and are available from 800 A to 6000 A

4) Automatic Static Transfer Switches (ASTS) perform a similar function as an ATS, only much more quickly. They were developed to switch electronic loads so quickly from one source to another that the load was not impacted by the transfer; it continues to operate as if no transfer had occurred. For low-voltage applications, a pair of silicon controlled rectifiers (SCRs) in a back-to-back configuration is used for each source. In medium-voltage applications, a number of SCRs are used in series for each direction of the current. ASTS are most often used in critical applications to provide UPS power from two sources. For most types of ASTSs, a bypass is provided using molded case switches or circuit breakers, so maintenance and testing can be performed on the ASTS without impacting the load that the ASTS feeds.

These switches are applied to provide protection against failure of the normal service. The transfer switch's control logic usually includes full-phase close differential voltage sensing of the normal source, voltage and frequency sensing of the emergency source, time delays for programmed operation, and in-phase monitoring for motor load transfer. In addition to utility failures, continuity of power to critical loads can also be disrupted by the following:

a) An open circuit within the building area on the load side of the incoming service

b) Overload or fault conditions

c) Electrical or mechanical failure of the electric power distribution system within the building

Therefore, many engineers advocate the use of lower-current-rated transfer switches located near the load rather than one large transfer switch at the point of incoming service. For critical applications where load interruptions must be minimized, transfer switches are available with built-in bypass/isolation switches to enable maintenance without any load interruption. Other types provide closed transition operation to momentarily parallel the sources for load transfer without interruption. For additional information, see IEEE Std 446™-1995 (*IEEE Orange Book*™).

4.4 Fuses

4.4.1 Types and rating basis

A fuse is an overcurrent-protective device with a circuit-opening fusible part that is heated and severed by the passage of overcurrent through it. Fuses are available in a wide range of voltage, current, and interrupting ratings, current-limiting types, and for indoor and outdoor applications.

Fuses rated greater than 600 V have an interrupting capability based on asymmetrical current, although their published ratings are expressed in symmetrical amperes. Current-limiting fuses interrupt a short circuit within the first half-cycle, and their equivalent asymmetrical rating includes a 1.6 multiplier to provide for the maximum expected current asymmetry.

Standard fuses without current-limiting capabilities are widely applied above 600 V. They are generally available in higher current ratings, but lower interrupting ratings, than current-limiting fuses.

Fuse ratings for 600 V and below are also published as symmetrical current values. These current-limiting fuses are extremely fast in operation at very high values of fault current, and act to limit the current in less than one-quarter cycle to a value well below the available peak short-circuit current. Several types of current-limiting fuses for 600 V and below are now available for ac service with interrupting ratings as high as 300 000 A rms symmetrical. For more information on fuses, see IEEE Std 141™-1993 (*IEEE Red Book*™), Chapter 5.

4.4.2 Application considerations

There is no general rule for deciding whether to use fuses or a circuit breaker. The designer's decision should be based on the demands of the particular application. The following considerations may be of assistance to the designer:

a) Interrupting ratings. Current-limiting fuses with 300 000 A rms symmetrical ratings are available for 600 V and below applications.

b) Component protection.

  1) Current-limiting fuses permit minimal short-circuit current let-through, thus helping to minimize damage to lower interrupting capacity-rated and withstand-rated components.

  2) Current-limiting fuses can cause transient voltages in clearing faults that may be detrimental to the system components, such as motors, surge arresters, etc. However, techniques are available to determine the suitability of equipment during the engineering phase.

  3) Fuses, in conjunction with shunt-trip switches and ground-fault sensing systems, can provide sensitive protection.

c) Selective coordination. Fuse time—current clearing curves are accurate, and fuses' characteristics usually do not change over time. Selective coordination can be achieved by referring to

manufacturers' published fuse ratio charts. By adhering to these recommended ratios and exercising sound engineering judgment, coordination between different types of protective devices can be achieved. Also, protective coordination studies may be done on computers. Protective coordination software exists which contains libraries of fuse manufacturers' curves and other protective devices.

d) Space requirements. Fusible switching devices require more space than circuit breakers.

e) Economics. Initial capital cost and maintenance costs are lower for fusible equipment.

f) Automatic switching. Fuses alone are not capable of automatic switching, but can be installed in suitable shunt-trip equipped switches to provide this service. Care must be exercised in applying a shunt-tripped switch. If the shunt-trip is actuated by a protective of phase failure relay, the switch must be capable of interrupting the fault duty to which it may be subjected, and the switch shall be prevented from opening when the fault current exceeds the interrupting capability of the switch.

4.5 Circuit breakers

A circuit breaker is a device designed to open and close a circuit by non-automatic means, and to open the circuit automatically on a predetermined overload of current without damage to itself when properly applied within its rating. Circuit breakers are required to operate infrequently, although some classes of circuit breakers are suitable for more frequent operation. The interrupting and momentary ratings of a circuit breaker must be equal to or greater than the available system short-circuit currents.

To provide essential switching flexibility and circuit protection, power circuit breakers are used on medium- and low-voltage systems of utility and industrial distribution circuits.

Circuit breakers are available for the entire voltage range. They may be furnished single-, double-, triple-, or four-pole, and arranged for indoor or outdoor use. SF_6 gas-insulated circuit breakers are available for medium and high voltages, such as gas-insulated substations.

4.5.1 Circuit breakers over 600 V

The close-and-latch rating and current-interrupting capabilities are very important factors for use in the application of circuit breakers over 600 V. The close-and-latch capability is a measure of the equipment's ability to withstand the mechanical stresses produced by the asymmetrical short-circuit current during the first cycle without mechanical damage, and is normally expressed as total rms current. An asymmetrical current consists of a dc component superimposed on an ac component. The dc component decays with time, depending upon the resistance and reactance, or the X/R ratio of the circuit. The initial value of the dc component of the short-circuit current depends on the point of the normal voltage wave at which the fault occurs. The procedure to be used for short-circuit selection of power circuit breakers in the over 600 V class is covered in IEEE Std 141™-1993 (*IEEE Red Book*™), Chapter 5. Application data can be found in IEEE Std C37.010™-1999.

For the rating of power circuit breakers in the over 600 V class, refer to IEEE Std C37.06™-2009. Circuit breakers currently being manufactured are rated on the symmetrical basis. In specifying these circuit breakers, consideration should be given to the related values and required capabilities listed as headings in Table 2 and Table 3. These tables list preferred ratings for Class S1 (indoor oilless) circuit breakers. These ratings are applicable for service at altitudes up to 1000 m (3300 ft). For service beyond 1000 m, de-rating factors must be applied in accordance with IEEE Std C37.04™-1999.

In 2000, a significant change was made to the preferred ratings in IEEE Std C37.06™. Prior to this revision, the rating structure of all power circuit breakers rated over 600 V were those that were first established for air-magnetic type interrupters. The ratings were classified by a nominal MVA rating as the capability of the interrupters followed a constant MVA characteristic, that is, as the applied voltage was

decreased from the maximum voltage rating of the breaker, the interrupting current rating could be increased proportionately, up to the maximum short-circuit rating of the breaker. The relationship between the short-circuit rating at maximum voltage and the maximum short-circuit rating was indicated by a voltage range factor, K. In most cases K was equal to 1.30. On the other hand, vacuum and SF_6 breakers do not exhibit a constant MVA characteristic. Rather, their maximum short-circuit current rating is applicable to the entire range of voltages to which they can be applied. IEEE Std C37.06™-2000 was revised to reflect this. The MVA class designations and voltage range factor were removed. While many breakers rated under the previous rating structure are still in service and since it is still possible to specify breakers using the old rating structure, the preferred ratings of IEEE Std C37.06™-1987 are provided in Table 4 for reference purposes.

In switchgear manufactured through the 1980s, power circuit breakers used for applications through 15 kV have been predominantly of the air-magnetic type; however, vacuum and SF_6 types are now used almost exclusively for new installations. For voltages above 15 kV, the available types of circuit breakers include oil, compressed air or gas, and vacuum interrupters. In general, vacuum power circuit breakers are applied in accordance with the specific continuous and short-circuit current requirements in the same manner as air-magnetic power circuit breakers. However, under certain conditions vacuum interrupters have characteristics that are different from air-magnetic power circuit breakers. Vacuum interrupters will sometimes, in special applications, force a premature current zero by opening ("chopping") the circuit in an unusually short time. When this occurs, a higher than normal transient recovery voltage occurs that can be of a magnitude that will impose excessive dielectric stress on the connected equipment. In some equipment, this magnitude may be greater than the basic impulse insulation level of any connected device, and failure may result.

When applying vacuum power circuit breakers, the following precautions should be taken:

a) Switching unloaded transformers. When switching power transformers that are unloaded, that is, interrupting just the small magnetizing current on an infrequent basis (less than 50 operations per year), and where the basic impulse insulation level is 95 kV or higher, generally no special attention is required. However, should either a dry-type transformer be involved with less than a 95 kV basic impulse insulation level rating, or all switching be highly repetitive, then the applications should be checked with the transformer manufacturer.

b) Switching loaded transformers. When a power transformer has a permanently connected load in kilovoltamperes of 5% or more of its nameplate rating, generally no special consideration is needed.

c) Switching motors. When vacuum power circuit breakers are utilized to switch motors, the standard rotating-machine protection package of capacitors and surge arresters should be considered if required by the manufacturer's design.

Transient recovery voltage (TRV) parameters remain an important consideration for proper application. Transformer-limited faults and air-core reactors are known to produce TRV stress exceeding TRV limits established for breakers. Vacuum circuit breakers are typically less sensitive to excessive TRV stress. SF_6-type units typically meet requirements for outdoor service. Circuits shall meet the TRV requirements as established by IEEE Std C37.04™-1999 and ANSI C37.06-2009. For guidance, consult IEEE Std C37.011™-2011 and the circuit breaker manufacturer.

Table 2—Preferred ratings for Class S1 (indoor) circuit breakers for cable systems[a,b]

Rated maximum voltage U_r (1) (kV, rms)	Rated continuous current (4) (A, rms)	Rated short-circuit and short-time current* (kA, rms)	Rated interrupting time (2) (ms)	Maximum permissible tripping time delay Y (sec)	Rated closing and latching current (3) (kA, peak)
4.76	1200, 2000	31.5	50 or 83	2	82
4.76	1200, 2000	40	50 or 83	2	104
4.76	1200, 2000, 3000, 4000	50	50 or 83	2	130
4.76	1200, 2000, 3000, 4000	63	50 or 83	2	164
8.25	1200, 2000, 3000	40	50 or 83	2	104
15	1200, 2000	20	50 or 83	2	52
15	1200, 2000	25	50 or 83	2	65
15	1200, 2000	31.5	50 or 83	2	82
15	1200, 2000, 3000	40	50 or 83	2	104
15	1200, 2000, 3000	50	50 or 83	2	130
15	1200, 2000, 3000, 4000	63	50 or 83	2	164
27	1200	16	50 or 83	2	42
27	1200, 2000, 3000	25	50 or 83	2	65
38	1200	16	50 or 83	2	42
38	1200, 2000	25	50 or 83	2	65
38	1200, 2000, 3000, 4000	31.5	50 or 83	2	82
38	1200, 2000, 3000, 4000	40	50 or 83	2	104

[a] Numbers in parenthesis refer to the items in 4.5.1.1.
[b] For preferred capacitance current switching ratings, see Table 3.

Source: Based on IEEE Std C37.06™-2009

4.5.1.1 Information for Table 2

1) The voltage ratings are based on ANSI C84.1-2006 [B2] where applicable and are the maximum voltages for which the circuit breakers are designed and are the upper limit for operation.

2) The ratings in this column are the maximum time interval to be expected during a circuit-breaker opening operation between the instant of energizing the trip circuit and the interruption of the main circuit on the primary arcing contacts under certain specified conditions. The values may be exceeded under certain conditions as specified in IEEE Std C37.04b™-2008, subclause covering rated interrupting time.

3) For 60 Hz, rated closing and latching current (kA, peak) of the circuit breaker is 2.6 times the rated short-circuit current. (If expressed in terms of kA, rms total current, the equivalent value is 1.55 times rated short-circuit current.) For 50 Hz, the kA peak is 2.5 times the rated short-circuit current and the rms total current is 1.47 times the rated short-circuit current.

4) The traditional North American continuous current rating of 1200 A has been retained in this standard, while IEC prefers the continuous current rating of 1250 A. It is possible that the continuous current rating might be changed to 1250 A in a future edition.

Table 3—Preferred capacitance current switching ratings for Class S1 circuit breakers for cable systems below 100 kV[a]

Rated maximum voltage Ur	Rated continuous current	Class C0 (1) (2)		Class C1 and C2 (2) (4)		Class C1 and C2 (2) (4) (7)						
		Rated cable charging current	Rated isolated capacitor bank current	Rated isolated capacitor bank current	Rated cable charging current	Back-to-back capacitor bank switching					
						Rated capacitor bank current (6)	Rated in-rush current (3) (5)					
							Preferred rating (8)		Alternate 1 rating (8)		Alternate 2 rating (8)	
							Peak value	Frequency	Peak value	Frequency	Peak value	Frequency
kV, rms	A, rms	A, rms	A, rms	A, rms	A, rms	A, rms	kA, peak	kHz	kA, peak	kHz	kA, peak	kHz
4.76	1200	10	400	630	10	630	15	2	6	0.8	14	1.8
4.76	2000	10	400	1000	10	1000	15	1.3	6	0.5	17	1.4
4.76	3000	10	400	1600	10	1600	25	1.3	6	0.3	22	1.1
8.25	1200	10	250	630	10	630	15	2	6	0.8	18	2.4
8.25	2000	10	250	1000	10	1000	15	1.3	6	0.5	22	1.9
8.25	3000	10	250	1600	10	1600	25	1.3	6	0.3	28	1.5
15	1200	25	250	630	25	630	15	2	6	0.8	24	3
15	2000	25	250	1000	25	1000	15	1.3	6	0.5	30	3
15	3000	25	250	1600	25	1600	25	1.3	6	0.3	38	2
15	4000	25	250	1600	25	1600	25	1.3	6	0.3	38	2
27	3000	31.5	160	250	31.5	250	15	4.3	6	2	19	7
27	3000	31.5	160	400	31.5	400	15	4.3	6	1.3	25	5
27	4000	31.5	160	630	31.5	630	25	4.3	6	0.8	31	4
38	4000	50	100	250	50	250	20	4.3	6	2	21	7
38	4000	50	100	630	50	630	20	4.3	6	0.8	33	5
38	4000	50	100	1000	50	1000	20	4.3	6	0.5	43	4

Source: Based on IEEE Std C37.06™-2009
[a]Numbers in parenthesis refer to the items in 4.5.1.2.

4.5.1.2 Information for Table 3

1) For class C0 (general-purpose) circuit breakers, no ratings for back-to-back capacitor switching applications are established. The capacitor bank or cable shall be "isolated" as defined in 5.11 of IEEE Std C37.04a™-2003.

   For class C0 (general-purpose) circuit breakers exposed to transient in-rush currents from nearby capacitor banks during fault conditions, the capacitance transient in-rush peak current on closing shall not exceed the lesser of either (1.41 times rated short-circuit current), or 50 000 A peak. The product of transient in-rush current peak and transient in-rush current frequency shall not exceed 20 kA-kHz. The service capability and circuit-breaker condition for this duty shall be as defined in IEEE Std C37.012™-2005, 4.2.1.1 (capacitor bank) or 4.2.2.1 (cable).

2) The circuit breaker shall be capable of switching any capacitive current of the ratings listed in the selected rating column by the user, in the preceding tables, at any voltage up to the rated maximum voltage.

3) The rated transient in-rush current peak is the highest magnitude of current that the circuit breaker shall be required to close at any voltage up to the rated maximum voltage and shall be as determined by the system and unmodified by the circuit breaker. The rated transient in-rush current frequency is the highest frequency that the circuit breaker shall be required to close at 100% rated back-to-back capacitor switching in-rush current rating.

4) For application at less than 100% of rating, the product of the in-rush current peak and frequency shall not exceed the product of the rated transient current peak and the rated transient in-rush current frequency. (This product quantifies the maximum rate of change of in-rush current and the minimum inductance between the banks or cables.)

5) For circuit breakers identified as a Class C1 or C2 (formerly referred to as definite purpose), the manufacturer shall state the in-rush current peak and frequency at which the circuit breaker meets Class C1 or C2 performance. The stated in-rush current peak and frequency may be the preferred values from Table 4 or other values as determined by the manufacturer.

6) The transient in-rush current in circuit breakers applied in GIS substations has a very high equivalent frequency (up to the MHz range, depending on the bus length) with an initial peak current of several thousand amperes (depending on the surge impedance of the bus). For reference, see IEEE Std C37.012™-2005. Contact the manufacturer to determine the ability of the circuit breaker to withstand these in-rush current stresses.

7) Tests to prove Class C2 have to be performed according to the requirements of Table 2 of IEEE Std C37.09a™-2005. Tests to prove Class C1 have to be performed according to the requirements of Table 2A of IEEE Std C37.09a™-2005.

8) The preferred ratings and alternates 1or 2 ratings have different values. These values are for qualification of circuit-breaker capacitance switching according to their capabilities. The preferred ratings list the previous values indicated in ANSI C37.06-2009 and represent the standard values for circuit breakers. Alternate 1 ratings were added in particular for some ratings of vacuum and some other circuit breakers, and alternate 2 ratings represent the exceptional maximum values as seen by users and manufacturers in some world-wide applications. As of the time of the printing, only synthetic tests for alternate 2 are available in some laboratories.

9) For Class C1 and C2 circuit breakers exposed to transient in-rush currents from nearby capacitor banks during fault conditions, the capacitance transient in-rush peak current shall not exceed the close and latch (peak withstand) capability of the circuit breaker. This is considered an infrequent event, and therefore the circuit breaker should be expected to handle this duty twice in the lifetime of the circuit breaker without requiring maintenance of the contacts.

Table 4—Preferred ratings for indoor oil-less breakers (MVA rated)[a]

Rated maximum voltage (1) (kV, rms)	Rated voltage range factor K (2)	Rated continuous current at 60 Hz (3) (A, rms)	Rated short-circuit current[b] (at rated maximum kV) (4)(5)(6)(9) (kA, rms)	Rated interrupting time (7) (cycles)	Rated maximum voltage divided by K (kV, rms)	Maximum symmetrical interrupting capability and rated short-time current (4)(5)(8) (kA, rms)	Closing and latching capability 2.7K times rated short-circuit current (4) (kA, crest)
4.76	1.36	1200	8.8	5	3.5	12	32 97 132
4.76	1.24	1200, 2000	29	5	3.85	36	
4.76	1.19	1200, 2000, 3000	41	5	4.0	49	
8.25	1.25	1200, 2000	33	5	6.6	41	111
15.0	1.30	1200	18	5	11.5	23	62 97 130
15.0	1.30	1200, 2000	28	5	11.5	36	
15.0	1.30	1200, 2000, 3000	37	5	11.5	48	
38.0	1.65	1200, 2000, 3000	21	5	23.0	35	95
38.0	1.0	1200, 3000	40	5	38.0	40	108

NOTE 1—For service conditions, definitions, and interpretation of ratings, tests, and qualifying terms, see IEEE Std C37.04™-1979, IEEE Std C37.09™-1979, and IEEE Std C37.100™-1992.

NOTE 2—The interrupting ratings are for 60 Hz systems. Applications on 25 Hz systems should receive special consideration.

NOTE 3—Current values have been rounded off to the nearest kiloampere (kA) except that two significant figures are used for values below 10 kA.

Source: Based on IEEE Std C37.06™-1987 [B24]

[a]Numbers in parenthesis refer to the items in 4.5.1.3.

[b]For the related required capabilities associated with the rated short-circuit current of the circuit breaker, see d) in 4.5.1.3.

4.5.1.3 Information for Table 4

a) The voltage rating is based on ANSI C84.1-1989, where applicable, and is the maximum voltage for which the breaker is designed and the upper limit for operation.

b) The rated voltage range factor, K, is the ratio of rated maximum voltage to the lower limit of the range of operating voltage in which the required symmetrical and asymmetrical current-interrupting capabilities vary in inverse proportion to the operating voltage.

c) The 25 Hz continuous current ratings in amperes are given herewith following the respective 60 Hz rating: 600 to 700; 1200 to 1400; 2000 to 2250; 3000 to 3500.

d) Related required capabilities. The following related required capabilities are associated with the short-circuit current rating of the circuit breaker.

1) Maximum symmetrical interrupting capability (kA, rms) of the circuit breaker is equal to K times rated short-circuit current.

2) 3 s short-time current-carrying capability (kA, rms) of the circuit breaker is equal to K times rated short-circuit current.

3) Closing and latching capability (kA, rms) of the circuit breaker is equal to 1.6 K times rated short-circuit current. If expressed in peak amperes, the value is equal to 2.7 K times rated short-circuit current.

4) 3 s short-time current-carrying capability and closing and latching capability are independent of operating voltage up to and including rated maximum voltage.

e) To obtain the required symmetrical current-interrupting capability of a circuit breaker at an operating voltage between $1/K$ times rated maximum voltage and rated maximum voltage, the following formula shall be used:

$$\begin{pmatrix} \text{Required symmetrical current} \\ \text{interrupting capability} \end{pmatrix} = \begin{pmatrix} \text{rated short} \\ \text{circuit current} \end{pmatrix} \times \frac{(\text{rated maximum voltage})}{(\text{operating voltage})} \qquad (1)$$

For operating voltages below $1/K$ times rated maximum voltage, the required symmetrical current interrupting the circuit breaker shall be equal to K times rated short-circuit current.

f) With the limitation stated in 5.10 of IEEE Std C37.04™-1979, all values apply for polyphase and line-to-line faults. For single phase-to-ground faults, the specific conditions stated in 5.10.2.3 of IEEE Std C37.04™-1979 apply.

g) The ratings in this column are on a 60 Hz basis and are the maximum time interval to be expected during a breaker opening operation between the instant of energizing the trip circuit and interruption of the main circuit on the primary arcing contacts under certain specified conditions as specified in 5.7 of IEEE Std C37.04™-1979.

h) Current values in this column are not to be exceeded even for operating voltages below $1/K$ times rated maximum voltage. For voltages between rated maximum voltage and $1/K$ times rated maximum voltage, follow e) above.

i) Rated permissible tripping delay time (Y) = 2 s.

j) The rated values for $T2$ are not standardized for indoor oilless circuit breakers; however, $E2 = 1.88$ times rated maximum voltage; $E2$ = transient recovery voltage; $T2$ = rated time to point P µs.

4.5.2 Circuit breakers of 600 V and below

Circuit breakers rated 600 V and below are divided into two basic classes and three types:

Classifications:

a) Low-voltage power circuit breaker class

b) Molded-case circuit breaker class

Types: The first two types are derived from the above classifications. The third type offers features from both the first and the second class.

a) Low-voltage power circuit breakers (LVPCBs)

b) Molded-case circuit breakers (MCCBs)

c) Insulated-case circuit breakers (ICCBs)

4.5.2.1 Low-voltage power circuit breakers (LVPCBs)

Power circuit breakers of 600 V and below have historically been open-construction assemblies on metal frames with all parts designed for accessible maintenance, repair, and ease of replacement. The latest models utilize molded case designs that completely enclose the mechanism and primary components (see Figure 1). They are intended for service in switchgear compartments or other enclosures of dead-front construction. Tripping units are field-adjustable over a wide range and are interchangeable within their frame sizes. The tripping units used are the electromagnetic overcurrent direct-acting type, solid-state type, and microprocessor-based units with various selectivity and additional monitoring and network communication capabilities.

These types of breakers can be used with integral current-limiting fuses in drawout construction to meet interrupting current requirements up to 200 000 A rms symmetrical. When part of the circuit breaker, the fuses are combined with an integral-mounted open-fuse trip device to prevent single-phasing if one fuse should blow.

In current designs of power circuit breakers of 600 V and below, contacts often begin to part during the first cycle of short-circuit current but have a multicycle total clearing time. Consequently, these breakers should be designed to interrupt the maximum available quarter-cycle asymmetrical current. Power circuit breakers of 600 V and below are rated on a symmetrical current basis. The ability of the circuit breaker to interrupt the maximum available quarter-cycle asymmetrical current is indicated by the short circuit impedance X/R of the test circuit. Minimum test X/R ratios that the breaker designs must be subjected to are defined by the circuit breaker test standard. Provided that the circuit breakers are applied at a system location where the X/R ratio is equal to or lower than the X/R ratios at which they are tested, no further evaluation is necessary. (Note that caution should be applied when these power circuit breakers are supplied with short-time delay trips because increases in short-circuit stress on the breaker could result in both a lower breaker interrupting capacity rating and extensive equipment damage from exceeding withstand ratings. For more information consult manufacturers' literature.)

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Figure 1—Low-voltage power circuit breakers

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Figure 2—Molded-case circuit breakers

Power circuit breakers 600 V and below can be applied on a symmetrical basis to its nameplate rating up to X/R ratios of 6.6 for unfused breakers and up to X/R ratios of 4.9 for fused breakers. Power circuit breakers may be applied to systems with higher X/R ratios when applied in accordance with the application information provided in 9.1.4.4. of IEEE Std C37.13™-2008 and IEEE Std 1015™-2006 (*IEEE Blue Book™*).

Power circuit breakers are designed for periodic planned maintenance. This design permits higher endurance ratings and repetitive duty capabilities and some basis for a broader range of applications.

Manufacturers' publications give specific information on mechanical and electrical features of power circuit breakers 600 V and below. Refer to IEEE Std C37.13™-2008, ANSI C37.16-2009, and Table 5 for lists of standard ratings for 600 V and below circuit breakers. For service at altitudes above 6600 ft above sea level, de-rating factors must be applied in accordance with IEEE Std C37.13™-2008.

Unusual service conditions, as defined in IEEE Std C37.13™-2008, should be considered when applying power circuit breakers. Such conditions should be brought to the attention of the circuit breaker manufacturer at the earliest possible time.

4.5.2.2 Molded-case circuit breakers (MCCBs)

A molded-case circuit breaker (UL 489-2011) is a switching device and an automatic protective device assembled in an integral housing of insulating material. These breakers are generally capable of clearing a fault more rapidly than power circuit breakers and are available in the following general types:

a) Thermal magnetic. This type employs thermal tripping for overloads and instantaneous magnetic tripping for short circuits. These are the most widely applicable molded-case circuit breakers (see Figure 2).

b) Magnetic. This type employs only instantaneous magnetic tripping where only short-circuit interruption is required. The NEC recognizes adjustable magnetic types for motor circuit protection.

c) Integrally fused. This type combines regular thermal magnetic protection against overloads and lower value short-circuit faults with current-limiting fuses responding to higher short-circuit currents. Interlocks are provided to help ensure safe and proper operation.

d) High interruption rating. This fuseless type provides interrupting capabilities for higher short-circuit currents than do standard constructed thermal magnetic circuit breakers. This line incorporates sturdier construction of contacts and mechanism, plus a special high-impact molded casing.

e) Current-limiting. This type provides high interruption rating protection, plus it limits let-through current and energy to a value significantly lower than the corresponding value for a conventional molded-case circuit breaker. Clearing time is also limited, and restoration of service is possible by resetting without replacement of any fusible elements or other parts.
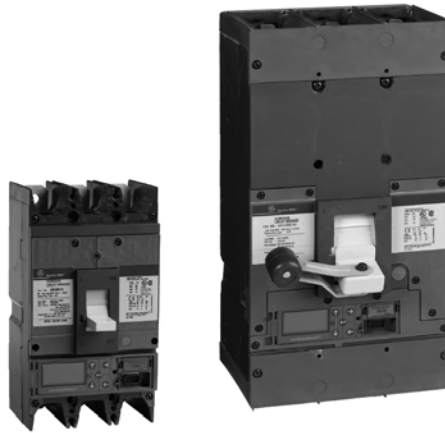
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Figure 3—Fully adjustable molded-case circuit breakers with electronic trip devices

With the advent of electronic trip devices being incorporated into molded-cased circuit breakers, the possibility for coordination with power circuit breakers is improved. The electronic trips of molded-case circuit breakers can be basic models with interchangeable rating plugs and adjustable instantaneous trips, or they may also be fully adjustable and provide short-time and ground-fault protection. This latter category is generally available in frame ratings of 400 A and larger, but may be available in frame ratings as low as 150 A, depending on the manufacturer. The fully adjustable electronic trips may also provide optional advanced protection, such as zone selective interlocking, and power metering and network communications. The fully adjustable molded-case circuit breaker still requires close scrutiny for proper application. Molded-case circuit breakers have an instantaneous override even when they are set on short-time delay. When a load-side (downstream) circuit breaker sees a large fault, not only will it trip, but if the fault exceeds the instantaneous setting of the line-side (upstream) circuit breaker, it might also trip. For system integrity, care must be exercised to ensure that coordination is maintained with line-side (upstream) devices and that load-side (downstream) equipment withstand ratings are not exceeded. Manufacturers' testing has identified combinations of circuit breakers whose instantaneous elements will be selectively coordinated up to a maximum short-circuit level. Consult manufacturers' literature for this information.

Molded-case circuit breakers generally are not designed to be maintained in the field as are power circuit breakers. Many molded-case breakers are sealed to prevent tampering, thereby precluding inspection of the contacts. In addition, replacement parts are not generally available. Manufacturers recommend total replacement of the molded-case circuit breaker if a defect appears, or if the unit begins to overheat. Molded-case circuit breakers, particularly the larger sizes, are not suitable for repetitive switching. Maintenance should be performed upon molded-case circuit breakers after they experience a fault that was near its interruption rating. It is important to recognize that differences in test criteria between power circuit breakers and molded-case circuit breakers can be significant in the application of circuit breakers at or near their interrupting rating. A combination of circumstances can reduce the performance of molded-case circuit breakers to less than adequate if they are applied at or near their interrupting rating on a par with power circuit breakers.

4.5.2.3 Insulated-case circuit breakers (ICCBs)

Insulated-case circuit breakers utilize characteristics of design from both power- and molded-case types. The basic requirements of these circuit breakers are governed by the same standard as molded-case circuit breakers, UL 489. The frame size of this type of breaker is larger than the frame size for molded-case breakers. The trip unit can be interchanged, and the breakers can be designed for fixed-mounting as well as with drawout configuration. In general, interruption of ICCBs is not fast enough to be a current-limiting type. Insulated-case circuit breakers are partially field-maintainable. The circuit breaker must be capable of

closing, carrying, and interrupting the highest fault current within its rating at that location. It is essential to select a circuit breaker whose interrupting rating at the circuit voltage is equal to or greater than the available short-circuit current at the point of installation. The procedure to be used for selection of power circuit breakers of 600 V and below with the proper interrupting rating is covered in IEEE Std 141™-1993 (*IEEE Red Book*™) Chapter 6.

Table 5—Preferred ratings for low-voltage ac power circuit breakers with direct-acting phase trip elements

Frame size	Rated maximum voltage	Three-phase short-circuit rating (kA) / Short-time current rating (kA) [a] (see Note 4)			Range of trip device current ratings (amperes) (see Note 1, Note 2, and Note 3)
		Minimum short circuit rating (kA)	Maximum short circuit current		
			Without instantaneous direct-acting trips (kA)	With instantaneous direct-acting trips (kA)	
600 [b]	254	22	22	42	300 to 600
800	254	22	85	200	60 to 800
1600	254	42	85	200	300 to 1600
2000	254	42	85	200	750 to 2000
3000 [b]	254	65	65	85	1200 to 3000
3200	254	65	100	200	1200 to 3200
4000	254	85	100	200	1600 to 4000
5000	254	85	100	200	3200 to 5000
6000	254	85	100	200	3200 to 6000
600 [b]	508	22	22	30	300 to 600
800	508	22	85	200	60 to 800
1600	508	42	85	200	300 to 1600
2000	508	42	85	200	750 to 2000
3000 [b]	508	65	65	65	1200 to 3000
3200	508	65	100	200	1200 to 3200
4000	508	85	100	200	1600 to 4000
5000	508	85	100	200	3200 to 5000
6000	508	85	100	200	3200 to 6000
600 [b]	600	22	22	22	300 to 600
800	600	22	85	200	60 to 800
1600	600	42	85	200	300 to 1600
2000	600	42	85	200	750 to 2000
3000 [b]	600	65	65	65	1200 to 3000
3200	600	65	100	200	1200 to 3200
4000	600	85	100	200	1600 to 4000
5000	600	85	100	200	3200 to 5000
6000	600	85	100	200	3200 to 6000

NOTE 1—Based on manufacturers' literature.

NOTE 2—The continuous current rating for an ac power circuit breaker with an electronic trip system shall be one of the following preferred values: 100 A, 150 A, 200 A, 400 A, 600 A, 800 A, 1200 A, 1600 A, 2000 A, 3000 A, 3200 A, 4000 A, 5000 A, or 6000 A. Consult manufacturers' literature.

NOTE 3—The minimum setting for long-time protection is typically 50% of the continuous current capability of the trip device.

NOTE 4—Ratings in this column are rms symmetrical values for single-phase (2-pole) circuit breakers and three-phase average rms symmetrical values of three-phase (3-pole) circuit breakers. When applied on systems where rated maximum voltage may appear across a single pole, the short-circuit current ratings are 87% of these values. See IEEE Std C37.13™-2008.

Source: Based on data taken from IEEE Std C37.16™-2009.

[a] The preferred rated short-circuit current shall be one of the following values: 22 kA, 30 kA, 42 kA, 50 kA, 65 kA, 85 kA, 100 kA, 130 kA, 150 kA, or 200 kA.

[b] Preferred ratings for 600 A and 3000 A frame sizes are provided for historical reference.

4.6 Service protectors

A service protector consists of a current-limiting fuse and non-automatic circuit-breaker-type switching device in a single enclosure. Stored energy operation provides for manual or electrical closing. The service protector, utilizing basic circuit-breaker principles, permits frequent repetitive operation under normal and abnormal current conditions up to 12 times the device's continuous-current rating. In combination with current-limiting fuses, it is capable of closing and latching against fault currents up to 200 000 A rms symmetrical. During fault interruption, the service protector will withstand the stresses created by the let-through current of the fuses.

Service protectors are available at continuous-current ratings of 800 A, 1200 A, 1600 A, 2000 A, 3000 A, 4000 A, 5000 A, and 6000 A for use on 240 Vac and 480 Vac systems, in two-pole and three-pole construction. An open-fuse trip device, which prevents the occurrence of single phasing after a fuse opening, is included in the design of the service protector.

5. Switchgear and switchboards

5.1 General discussion

Switchgear is a general term that describes switching and interrupting devices, either alone or in combination with other associated control, metering, protective, and regulating equipment, which are assembled in one or more sections.

A power switchgear assembly consists of a complete assembly of one or more of the above-noted devices and main bus conductors, interconnecting wiring, accessories, supporting structures, and enclosure. Power switchgear is applied throughout the electric power system of an industrial plant, but is principally used for incoming line service and to control and protect load centers, motors, transformers, motor control centers, panelboards, and other secondary distribution equipment. Switchboards are similar to switchgear in functionality but are not designed to the same standards as switchgear.

Outdoor switchgear assemblies can be of the non-walk-in (without enclosed maintenance aisle) or walk-in (with an enclosed maintenance aisle) variety. Switchgear for industrial plants is generally located indoors for easier maintenance, avoidance of weather problems, and shorter runs of feeder cable or bus duct. In outdoor applications, the effect of external influences, principally the sun, wind, moisture, and local ambient temperatures, should be considered in determining the suitability and current-carrying capacity of the switchgear. Further information on outdoor applications is contained in IEEE Std C37.24™-2003.

In many locations, the use of lighter colored (non-metallic) paints will minimize the effect of solar energy loading to avoid de-rating of the equipment in outdoor locations. See IEEE Std C37.24™-2003.

5.2 Classifications

An open switchgear assembly is one that does not have an enclosure as part of the supporting structure. Since open switchgear assemblies are rarely used in industrial installations, consideration will be given to metal-enclosed assemblies only.

An enclosed switchgear assembly consists of a metal-enclosed supporting structure with the switchgear enclosed on the top and all sides with sheet metal (except for ventilating openings and inspection windows). Access within the enclosure is provided by doors or removable panels.

Metal-enclosed switchgear is universally used throughout industry for utilization and primary distribution voltage service, for ac and dc applications, and for indoor and outdoor locations.

5.3 Types of metal-enclosed switchgear

Specific types of metal-enclosed switchgear used in industrial and commercial facilities are defined as (1) metal-clad switchgear, (2) low-voltage power circuit breaker switchgear, (3) low-voltage switchboards, and (4) interrupter switchgear.

5.3.1 Metal-clad switchgear

Metal-clad switchgear is metal-enclosed power switchgear characterized by the following necessary features:

a)   The main circuit switching and interrupting device is of the removable type arranged with a mechanism for moving it physically between connected and disconnected positions, and equipped with self-aligning and self-coupling primary and secondary disconnecting devices.

b)   Major parts of the primary circuit, such as the circuit switching or interrupting devices, buses, voltage transformers, and control power transformers, are enclosed by grounded metal barriers. Specifically included is an inner barrier in front of, or as a part of, the circuit interrupting device to ensure that no energized primary circuit components are exposed when the unit door is opened (see Figure 5).

c)   All live parts are enclosed within grounded metal compartments. Automatic shutters prevent exposure of primary circuit elements when the removable element is in the test, disconnected, or fully withdrawn position.

d)   Primary bus conductors and connections are covered with insulating material throughout. For special configurations, insulated barriers between phases and between phase and ground may be specified.

e)   Mechanical interlocks are provided to help ensure a proper and safe operating sequence.

f)   Instruments, meters, relays, secondary control devices, and their wiring are isolated by grounded metal barriers from all primary circuit elements, with the exception of short lengths of wire associated with instrument transformer terminals.

g)   The door, through which the circuit-interrupting device is inserted into the housing, may serve as an instrument or relay panel and may also provide access to a secondary or control compartment within the housing (see Figure 4).

Auxiliary frames may be required for mounting associated auxiliary equipment, such as voltage transformers, control power transformers, etc.

The term metal-clad switchgear can be properly used only if metal-enclosed switchgear conforms to the foregoing specifications. All metal-clad switchgear is metal-enclosed, but not all metal-enclosed switchgear can be correctly designated as metal-clad. Metal-clad switchgear is designed and tested in accordance with IEEE Std C37.20.2™.

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Figure 4—Metal-clad switchgear
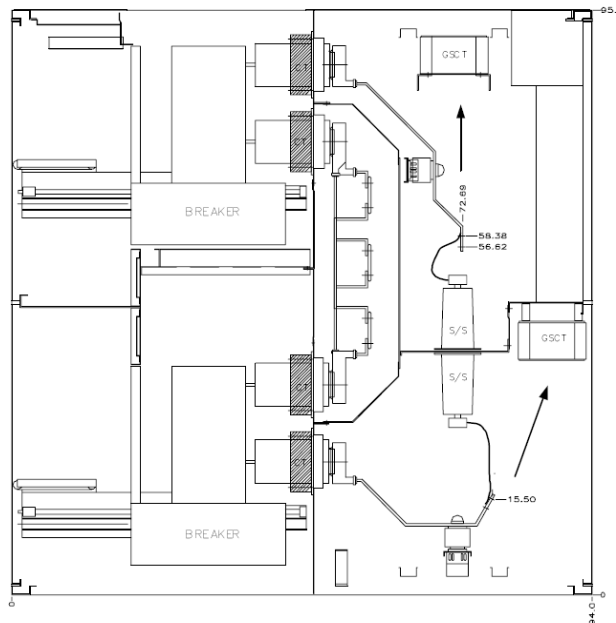
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Figure 5—Side view of typical metal-clad switchgear with "two-high" feeder breaker arrangement and cables exiting out top

5.3.2 Low-voltage power circuit breaker switchgear

Metal-enclosed power circuit breaker switchgear of 1000 Vac and below is metal-enclosed power switchgear, including the following equipment as required:

a) Power circuit breakers of 635 Vac and below (unfused) or 600 Vac and below (fused)

b) Non-insulated bus and connections (insulated and isolated bus is available)

c) Instrument and control power transformers

d) Instruments, meters, and relays

e) Control wiring and accessory devices

f) Cable and busway termination facilities

g) Shutters to automatically cover line-side contacts when the circuit breaker is withdrawn

Low-voltage metal-enclosed power switchgear must follow the requirements of IEEE Std C37.20.1™-2002. The NRTL listing standard is UL 1558. The power circuit breakers of 1000 V and below are contained in individual grounded metal compartments and controlled either remotely or from the front of the panels. The circuit breakers are required by IEEE Std C37.20.1™ to be drawout type (see Figure 6). The standard also contains specific requirements for mechanical interlocks that must be provided to help ensure a proper and safe operating sequence.

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**Figure 6—Low-voltage metal-enclosed switchgear,
with drawout circuit breaker in withdrawn position**

5.3.3 Low-voltage switchboards

Low-voltage switchboards of 600 V and below share the same functionality as metal-enclosed power switchgear, and can include the following equipment as required:

a)   Molded-case circuit breakers of 600 V and below

b)   Fusible load-break switches of 600 V and below

c)   Power circuit breakers of 600 V and below (generally unfused)

d)   Non-insulated bus and connections

e)   Instrument and control power transformers

f)   Instruments, meters, and relays

g)   Control wiring and accessory devices

h)   Cable and busway termination facilities

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Figure 7—Low-voltage switchboard, designed for front-only access to connections

Most low-voltage switchboards provided in the United States are designed and tested in accordance with UL 891 and NEMA PB2. Switching devices are typically circuit breakers listed to UL 489 or fusible switches listed to UL 977 or UL 98. Devices rated 1200 A and less can be provided in a "group-mounted" design, similar in appearance to a panelboard, with the panel assembly mounted in the switchboard enclosure and a deadfront covering all but the operating handles. Devices rated greater than 1200 A are individually mounted, and the switchboard design may allow for only one or two individually mounted devices per section.

The devices are stationary mounted with bolted power connections to the switchboard bussing. Group mounted devices may be available in a "plug-in" design that allows their removal and replacement without the need to unbolt the line-side connections. Individually mounted circuit breakers may be available in drawout mounting.

Most low-voltage switchboard designs provide front access for power cable terminations, which allow the switchboard enclosures to be located in front of walls. Most front access switchboard designs are not available with the same options for bus insulation or section barriers as available in low-voltage metal-enclosed switchgear. However, some manufacturers may provide rear access switchboards that share many of the same optional features as low-voltage metal-enclosed switchgear, the difference being that drawout mounting is not a standard requirement of these switchboards, UL 489 listed circuit breakers may be furnished rather than UL 1066 listed power circuit breakers, and fusible switches as well as circuit breakers may be installed.

5.3.4 Interrupter switchgear

Metal-enclosed interrupter switchgear is metal-enclosed power switchgear, including the following equipment as required:

a)   Interrupter switches or circuit breakers

b)   Power fuses (if required)

c)   Non-insulated bus and connections

d)   Instrument and control power transformers

e)   Control wiring and accessory devices

An example of a fused load interrupter switch is shown in Figure 8. The interrupter switches and power fuses may be of the stationary or removable type. For the removable type, mechanical interlocks are provided to facilitate a proper and safe operating sequence. Metal-enclosed interrupter switchgear is designed and tested in accordance with IEEE Std C37.20.3™-2001.

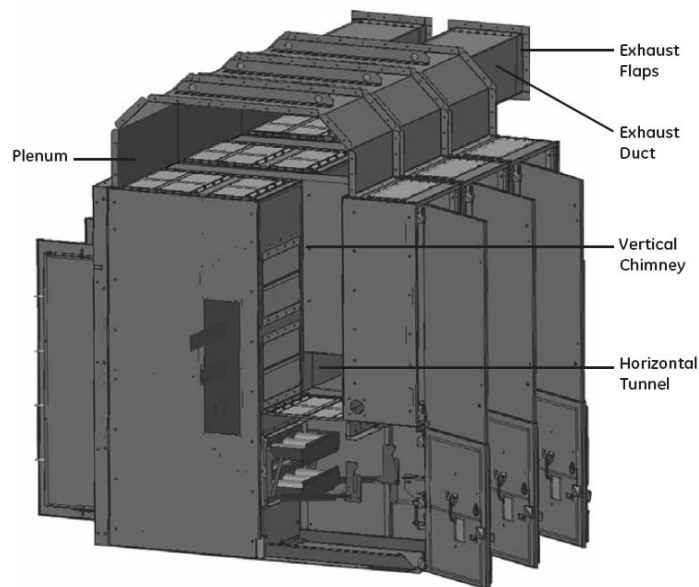### 5.3.5 Arc-resistant switchgear

Arc-resistant switchgear may be available to an extent in all forms of switchgear, low- and medium-voltage, metal-enclosed and metal-clad. It is most common in medium-voltage, but low-voltage designs have recently begun to be furnished by a few suppliers.

The goal of arc-resistant switchgear is to guard the heat and blast effects of an arc flash from causing injury to persons standing in close proximity to the enclosure. It does not necessarily do anything to prevent the arc from occurring or to limit the damage done to internal components. Arc-resistant switchgear is characterized by a heavy outer enclosure. Arc byproducts are allowed to escape in a controlled manner by specially designed vents located either on the top or the side of the enclosure. Since arc exhaust can contain toxic gasses, the vents on arc-resistant switchgear that is located indoors should be connected to ducts or plenums to direct the arc exhaust outside the building. These ducts must be specially designed so that they do not impede venting in any way, and they must be strong enough to contain the pressure exerted by the arc gases.

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Figure 8—Fused load interrupter switch

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Figure 9—Arc-resistant switchgear showing the plenum and exhaust system

All covers must be secured in place with all intended fasteners supplied by the manufacturer. Loss of a fastener could jeopardize the integrity of the enclosure. Opening a cover to perform a diagnostic test or other service work will also violate the arc-resistant design.

IEEE Std C37.20.7™-2007 defines the methods by which switchgear shall be tested for resistance to the effects of arcing due to internal faults. The test involves initiating an arcing short-circuit within the

switchgear assembly to see if the enclosure can contain the arc to the criteria listed in the standard. The arcing current is to be driven by preferably the rated maximum voltage of the equipment, although reduced voltages are permitted due to laboratory constraints. However, there are further stipulations that must be followed to prevent premature arc extinguishment should a reduced voltage test be performed. The test value of the short-circuit is calibrated by shorting out the incoming terminals of the equipment, and the shorting conductors are then removed for the test. The arc is initiated using a small metal wire that has been placed directly on the phase bus bar. The size of the wire will vary depending on the ANSI standard to which the switchgear is designed, but it will be either 2.6 mm diameter (#10 AWG) or 0.55 mm diameter (#24 AWG). The thermal effects of arc gasses are determined through indicators constructed of black cotton fabric mounted in a metal frame and placed both vertically and horizontally around the switchgear enclosure. No indicators may ignite as a result of escaping arcing gasses for the switchgear sample to pass the test. In addition, all covers and doors must remain latched and not open, although some bowing or distortion is allowed. No fragmentation of the enclosure during the duration of the test is allowed. The arcing must not burn through the enclosure. All ground connections must remain effective following the test.

IEEE Std C37.20.7™-2007 defines two accessibility types. Type 1 defines switchgear with arc-resistant designs or features at the freely accessible front of the equipment only. Type 2 defines switchgear with arc-resistant designs or features at the freely accessible exterior (front, sides, and rear) only.

A Canadian standard that defines similar accessibility types was developed by Electrical and Electronic Manufacturers Association of Canada (EEMAC). EEMAC standards are no longer actively supported, but neither have they been formally withdrawn. EEMAC Std G14-1 [B16] lists three accessibility types:

Type A, Switchgear with arc-resistant construction at the front only (corresponds to IEEE Std C37.20.7™-2007 Type 1)

Type B, Switchgear with arc-resistant construction at the front, back, and sides (corresponds to IEEE Std C37.20.7™-2007 Type 2)

Type C, Switchgear with arc-resistant construction at the front, back, and sides, and between compartments within the same cell or adjacent cells, with an exception that a fault in a bus bar compartment of a feeder cell is allowed to break into the bus bar compartment of an adjacent feeder cell.

Arc resistance must be qualified for both arcing short-circuit current and arc duration. The preferred rating for arcing short-circuit current is the rated short-time current of the equipment. The preferred time duration rating is 0.5 s. Any value is permitted, but the recommended minimum duration is 0.1 s and it is considered unnecessary to test for longer periods than 1.0 s. These ratings may be further qualified by the use of current limiting breakers or fuses and this must be so stipulated on the equipment nameplate.

5.4 Switchgear design features

The enclosures of switchgear, both low-voltage and medium-voltage types will be supplied with hinged covers on the front, but standard covers on the rear may be bolted in place. Rear covers may be supplied as one-piece, but two-piece covers, arranged vertically, may also be available. The smaller sized cover on the two–piece design is easier to remove and replace. Hinged rear covers are also an available option and the fastening methods available can vary from bolted fasteners to three-point latches. Hinged covers are preferred for making the equipment safer should it be necessary to open the rear covers while the equipment is energized. Thermal scanning of power cable terminations is a common reason for doing this. However, infrared camera ports can be mounted on the rear covers to make opening the doors for this task unnecessary.

Breaker lifting devices (Figure 10) are often required for the removal of breakers from their rails once they have been moved to the withdrawn position. Low-voltage switchgear assemblies can be supplied with a

top-mounted hoist that can travel the length of the switchgear. These hoists are available on indoor enclosures and protected-aisle type outdoor enclosures. They are not possible on drip-proof indoor enclosures or non-walk-in outdoor enclosures. For these applications, a floor-mounted hoist can be furnished.

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Figure 10 —Using an integrally-mounted hoist to more safely remove a circuit breaker from its drawout rails

"Racking" a breaker back and forth from the Connect to the Disconnect positions is typically performed manually with a detachable handcrank. However, there can be a risk of arc flash occurring during this operation, so optional remote racking operators have been developed by equipment suppliers to allow the operator to stand outside the flash protection boundary while performing this task. The remote racking operator (Figure 11) is a motor operator that is temporarily latched into place to the breaker where the racking operation is desired. The motor operator is plugged into a convenience outlet and has a pushbutton module for running the motor from a suitable distance, limited by the length of the cord that connects the pushbutton module to the motor operator.

Local operation of circuit breakers and switches also has some inherent risk to arc flash. Giving the operator the means to open or close the breaker from a distance outside the flash protection boundary makes the operation safer. To this end, electrically operated devices are preferred over those that are only manually operated. Control switches should be located away from the section containing the device being operated. Remote control panels are better, but the necessary wiring adds complexity and cost. However, the addition of network input/output modules to the switchgear and their connection to a supervisory control system can allow an operator the ability to monitor and control the switchgear from any location where there is a network jack into which a laptop computer can be plugged.

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Figure 11 —Remote racking a low-voltage circuit breaker

5.5 Ratings

The ratings of switchgear assemblies are designations of the operational limits of the particular equipment under specific conditions of ambient temperature, altitude, frequency, duty cycle, etc. Table 6 lists the rated voltages and insulation levels for ac switchgear assemblies discussed in this section. Rated voltages and insulation levels for dc switchgear assemblies can be found by referring to IEEE Std C37.20.1™-2002, IEEE Std C37.20.2™-1999, and IEEE Std C37.20.3™-2001. The definition of the ratings listed in Table 6 and others subsequently discussed, can be found in IEEE Std C37.100™-1992.

The short-circuit withstand level and duration capabilities of switchgear assemblies and metal-enclosed bus must be completely coordinated with the operating characteristics of the power system line-side interrupter.

The continuous-current rating of the switchgear main bus must be no less than that of the highest rated overcurrent device or through current to which it must be subjected. The rated continuous current of a switchgear assembly is the maximum current in rms amperes, at rated frequency, that can be carried continuously by the primary circuit components without causing temperatures in excess of the limits specified in IEEE Std 37.20.1™-2002. The standard ratings of the main bus in ac low-voltage switchgear are 600 A, 800 A, 1200 A, 1600 A, 2000 A, 3000 A, 3200 A, or 4000 A, and in dc low-voltage switchgear are 1600 A, 2000 A, 2500 A, 4000 A, 5000 A, 6000 A, 8000 A, 10 000 A, and 12 000 A (IEEE Std C37.20.1™-2002).

The continuous-current rating of the vertical and section bus riser shall be equal to the frame size of ac low-voltage power circuit breaker used except any modification required for cumulating loading of multiple breakers (IEEE Std C37.20.1™-2002).

The momentary and short-time short-circuit current ratings of power switchgear assemblies shall correspond to the equivalent ratings of the switching or interrupting devices used.

The limiting temperature for a power switchgear assembly or metal-enclosed bus (where applicable) is the maximum temperature permitted for the following:

a) Any component, such as insulation, buses, instrument transformers, and switching and interrupting devices.

b) Air in cable termination compartments.

c) Any non-current-carrying structural parts.

d) For the air adjacent to devices.

e) The operating temperature of the cable(s) connected to all switchgear termination lugs while at maximum cable loading must not exceed the rated temperature of the terminals.

The information regarding temperature limits of insulating materials (hottest spots), buses and connections (hottest spots), and temperature limitations for air surrounding devices within an enclosed assembly and surrounding insulated power cables can be obtained from IEEE Std C37.20.1™-2002. Similar information for switchboard is available in UL 891.

One important distinction between switchgear designed and tested per IEEE Std C37.20.1™-2002 and switchboards designed and tested per UL 891-2005 is the short-circuit test duration. The short-time current duty cycle required by IEEE Std C37.20.1™-2002 is two 0.5 s periods of current flow with a 15 s period of no current flow in between. In contrast, UL 891-2005 requires a short-circuit test duration of a minimum of 3 cycles (0.05 s at 60 Hz). This tends to require the use of instantaneous trips on circuit breakers, which can affect the ability to coordinate system overcurrent devices for selective operation. The longer short-time current duty cycle for switchgear allows circuit breakers to be furnished with adjustable delay short-time protection that facilitates selective operation of system overcurrent devices at short-circuit current levels.

Table 6— Rated voltages and insulation levels for ac switchgear assemblies

Rated voltage (rms)		Insulation levels (kV)		
Rated nominal voltage	Rated maximum voltage	Power frequency withstand (rms)	DC withstand (Note 1)	Impulse withstand
Metal-enclosed low-voltage power circuit breaker switchgear (in V)				
240	254	2.2	3.1	—
480	508	2.2	3.1	—
600	635	2.2	3.1	—
Metal-clad switchgear (in kV)				
4.16	4.76	19	27	60
7.2	8.25	36	50	95
13.8	15.0	36	50	95
20.7	27.0	60	Note 2	125
34.5	38.0	80	Note 2	150
Metal-enclosed interrupter switchgear (in kV)				
4.16	4.76	19	27	60
7.2	8.25	36	50	95
13.8	15.0	36	50	95
20.7	27.0	60	Note 2	125
34.5	38.0	80	Note 2	150
Station-type cubical switchgear (in kV) (Note 3)				
14.4	15.5	50	Note 2	110
34.5	38.0	80	Note 2	150
69.0	72.5	160	Note 2	350
NOTE 1—The column headed dc withstand is given as a reference only for those using dc tests to verify the integrity of connected cable installations without disconnecting the cables from the switchgear. It represents values believed the corresponding power frequency withstand test values specified for each voltage rating of switchgear. The presence of this column in no way implies any requirement for a dc withstand test on ac equipment or that a dc withstand test represents an acceptable alternative to the low-frequency withstand tests specified in this standard, either for design tests, production tests, conformance tests, or field tests. When making dc tests, the voltage should be raised to the test value in discrete steps and held for a period of 1 min.				

Table 6, continued
NOTE 2—The column headed dc withstand is given as a reference only for those using dc tests to verify the integrity of connected cable installations without disconnecting the cables from the switchgear. It represents values believed the corresponding power frequency withstand test values specified for each voltage rating of switchgear. The presence of this column in no way implies any requirement for a dc withstand test on ac equipment or that a dc withstand test represents an acceptable alternative to the low-frequency withstand tests specified in this standard, either for design tests, production tests, conformance tests, or field tests. When making dc tests, the voltage should be raised to the test value in discrete steps and held for a period of 1 min.
NOTE 3—Because of the variable voltage distribution encountered when making dc withstand tests, the manufacturer should be contacted for recommendations before applying dc withstand tests to the switchgear. Voltage transformers above 34.5 kV should be disconnected when testing with dc. See IEEE Std C57.13™-1993, Clause 8, and in particular, 8.8.2 (the last paragraph), which reads "Periodic kenotron tests should not be applied to transformers of higher than 34.5 kV voltage rating."
NOTE 4—Station type cubicle switchgear was deleted from IEEE Std C37.20.2™ in the 1999 revision. This information is provided as reference information for existing equipment.

Source: Table and notes based on IEEE Std C37.20.1™-2002, IEEE Std C37.20.2™-1999, and IEEE Std C37.20.3™-2001.

5.6 Application guides

After determining system requirements for continuity of service, reliability, security, and safety, the engineer should establish initial system capacity and provisions for future load growth.

From this data, the engineer can establish maximum fault duty and select the type of power switching apparatus for the primary and secondary distribution systems. For the primary system, the choice is between circuit breaker and switch-fuse combinations. For the secondary system, the choice is between fused and unfused power circuit breaker combinations and switch-fuse combinations.

The following steps are normally taken in applying switchgear equipment:

a) Develop a one-line diagram

b) Determine short-circuit rating

c) Determine rating of power switching apparatus

d) Select main bus rating

e) Select current transformers

f) Select voltage transformers

g) Select metering, relaying, and control power

h) Determine closing, tripping, and other control power requirements

i) Consider special applications

Metal-enclosed switchgear is available for application at voltages through 34.5 kV. Metal-clad switchgear is available for application at voltages from 2.4 kV through 34.5 kV; however, it is seldom used above 15 kV for economic reasons. Gas-insulated switchgear is available for higher voltage.

Metal-enclosed switchgear is adaptable to many applications because it is easily expanded and can be specified and designed with load location and load characteristics in mind. If metal-enclosed switchgear with drawout-interrupting devices is applied, maintenance is facilitated because of the accessibility of most components. On the average, metal-enclosed switchgear represents a small percentage of total plant cost.

Metal-enclosed switchgear is generally shipped factory-assembled and pretested and reduces the amount of expensive field assembly.

Essentially, all recognized basic bus arrangements, radial, double bus, circuit breaker and half, main, and transfer bus, sectionalized bus, synchronizing bus, and ring bus are available in metal-enclosed switchgear to ensure the desired system reliability and flexibility. A choice is made based on an evaluation of initial cost, installation cost, required operating procedures, and total system requirements.

The switchgear assembly should have momentary and short-time ratings equal, respectively, to the close-and-latch capability and short-time rating of the circuit breaker or short-circuit rating at the fused switch.

Current transformers (CTs) are used to develop scale replica secondary currents, separated from the primary current and voltage, to provide a readily usable current for application to instruments, meters, relays, and analog communication with computers.

Voltage transformers (VTs) are used to transform primary voltage to a nominal safer value, usually 120 V. The primary rating is normally that of the system voltage, although slightly higher ratings may be used (i.e., a 14 400 V rating on a 13 800 V nominal system). These transformers are used to isolate the primary voltages from the instrumentation, metering, and relaying systems, yet provide replica scale values of the primary voltage. All ratings, such as impulse, dielectric, etc., should be adequate for the purpose. IEEE Std 3004.1-2013[8] [B42] should be referred to for detailed information on the application of current and voltage transformers.

Standard air-magnetic or vacuum power circuit breakers are rated at 60 Hz but can be applied as low as 50 Hz without de-rating. For a 25 Hz application, however, there is a de-rating factor that should be applied to the circuit breaker interrupting rating. Equipment manufacturers should be consulted to determine the proper de-rating factor for low-frequency power switchgear applications.

The application of metal-enclosed switchgear in contaminated atmospheres may create many problems if adequate precautions are not taken. Typical precautions include, but are not limited to, the following:

— Location of equipment away from localized sources of contamination and potential sources of moisture, such as steam pipes and traps, water pipes, etc.

— Isolation of equipment through the use of air-conditioning or pressurization equipment

— Development of an appropriate supplemental maintenance program

— Maintenance of adequate spare-part replacements

5.7 Control power

Successful operation of switchgear embodying electrically operated devices is dependent on a reliable source of control power that will maintain voltage at all times at the terminals of all devices within their rated operating voltage range. See Table 7.

There are two primary uses for control power in switchgear: tripping power and closing power. Since an essential function of switchgear is to provide instant and unfailing protection in emergencies, the source of tripping power must always be available. The requirements for the security of the source of closing power are less rigid, and other options are available. For devices of 1000 V and below, manual closing for devices through 1600 A frame is a common practice.

Four practical sources of tripping power are as follows:

a) Direct current from a storage battery

b) Direct current from a charged capacitor, with the charge maintained under normal operating conditions by an ac source via a diode bridge

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[8] IEEE Std 3004.1™-2013 was approved on February 6, 2013.

c) Alternating current from the secondaries of current transformers in the protected power circuit

d) Direct or alternating current in the primary circuit passing through direct-acting trip devices (no longer a common method in modern equipment)

The first two sources in the list are the most commonly applied in medium-voltage switchgear. Where protective relays also rely on control power for their operation, the power supplies for these relays should also be supplied from a secure source of power. It is a common practice to connect the relay power supply to the trip circuit of the circuit breaker. However, this should not be done when the trip circuit is supplied using capacitor trips. Since the relay power supply constitutes a continuous load, it would immediately discharge the capacitor when there is a loss of the ac power that maintains charge on the capacitor, leaving no energy for tripping power. Storage batteries are the preferred source for these situations. However, if this is simply not practical for some reason, a small uninterruptible power supply, sized to power only the protective relay power supplies for the desired outage time, could be applied to maintain secure power and allow the capacitor trips to be used for tripping power only [B58].

Where a storage battery has been chosen as a source of tripping power, it can also supply closing power. The battery ampere-hour and in-rush requirements have been reduced considerably with the advent of the stored-energy spring mechanism closing on power circuit breakers through 34.5 kV. General distribution systems, whether ac or dc, cannot be relied upon to supply tripping power because outages are always possible. These are most likely to occur in times of emergency, when the switchgear is required to perform its protective functions.

Other factors influencing the choice of control power are as follows:

— Availability of adequate maintenance for a battery and its charger

— Availability of suitable housing for a battery and its charger

— Advantages of having removable circuit breaker units interchangeable with those in other installations

— Necessity for closing overcurrent devices with the power system de-energized

The importance of periodic maintenance and testing of the tripping power source cannot be overemphasized. The most elaborate protective relaying system is useless if tripping power is not available to open the overcurrent device under abnormal conditions. Alarm monitoring for abnormal conditions of the tripping source and for circuits is a general requirement.

Electrically operated motors, contactors, solenoids, valves, and the like, need not carry a nameplate voltage rating that corresponds to the nominal voltage rating shown in the table as long as these components perform the intended duty cycle (usually intermittent) in the voltage range specified.

Space heaters are supplied as a standard feature on outdoor metal-enclosed switchgear. Often ambient temperatures or other environmental conditions dictate the use of space heaters in indoor switchgear as well. When space heaters are furnished, they should be continuously energized from an ac power source. Since heaters are usually needed when the switchgear is out of service, a separate source of heater power is desirable.

Table 7—Preferred control voltages and their ranges for low-voltage power circuit breakers and ac power circuit protectors[a]

Nominal voltage	Voltage ranges[b,c,d,e,k]	
	Closing[m] and auxiliary functions	Tripping[m] functions
Direct current [f]		
24 [g]	—	14 to 28
48 [g]	38 to 56	28 to 56
125	100 to 140	70 to 140
250	200 to 280	140 to 280
	Voltage ranges [b,c,d,e,h,k]	
Nominal voltage (60 Hz)	Closing,[m] tripping, and auxiliary functions	
Alternating current—single phase		
120	104 to 127 [i, j]	
240	208 to 254 [i]	
480	416 to 508 [i]	
Alternating current—polyphase		
208Y/120	180Y/104 to 220Y/127	
240	208 to 254	
480	416 to 508	
480Y/277	416Y/240 to 508Y/292	

NOTE—See IEEE Std C37.13™-2008, IEEE Std C37.14™-2002 [B24], IEEE Std C37.18™-1979 [B26], and IEEE Std C37.29™-1981 [B28].

Source: Based on IEEE Std C37.16™-2009

[a] When measured at the control power terminals of the operating mechanisms with the maximum operating current flowing, nominal voltages and their permissible ranges for the control power supply of switching and interrupting devices shall be as shown above.

[b] Relays, motors, or other auxiliary equipment that function as a part of the control for a device shall be subject to the voltage limits imposed by this standard, whether mounted at the device or at a remote location.

[c] The performance capability of an individual device over the full range of closing, auxiliary, and tripping voltages specified here shall be as defined in the C37 standard that covers the particular device.

[d] Switchgear devices in some applications may be exposed to control voltages exceeding those specified here owing to abnormal conditions, such as abrupt changes in line loading. Such applications require specific study, and the manufacturer should be consulted. Also, application of switchgear devices containing solid-state control exposed continuously to control voltages approaching the upper limits of ranges specified here requires specific attention, and the manufacturer should be consulted before application is made. Mining circuit breakers may require control voltages as high as 325 Vdc.

[e] Some solenoid operating mechanisms are not capable of satisfactory performance over the range of voltage specified here; moreover, two ranges of voltage may be required for such mechanisms to achieve a satisfactory level of performance. For these solenoid-operated devices, the following table is applicable:

Rated voltage (dc)	Closing voltage ranges for power supply
125 V	90 V to 115 V or 105 V to 130 V
250 V	180 V to 230 V or 210 V to 260 V
230 V	190 V to 230 V or 210 V to 250 V

The preferred method of obtaining the double range of closing voltage is by use of tapped coils. Otherwise it will be necessary to designate one of the two closing voltage ranges listed above as representing the condition existing at the device location owing to battery or lead voltage drop or control power-transformer regulation. Also, caution should be exercised to ensure that the maximum voltage of the range used is not exceeded if the solenoid operator is energized during the time the station battery is on equalizing charge.

[f] It is recommended that the coils of closing, auxiliary, and tripping devices that are directly connected to one dc potential be connected to the negative control bus to minimize electrolytic deterioration.

[g] Twenty-four V tripping or 48 V tripping, closing, and auxiliary functions are recommended only when the device is located near the battery or where special effort is made to ensure the adequacy of conductors between battery and control terminals. Twenty-four V closing is not recommended.

[h] Includes supply for pump or compressor motors.

[i] Includes heater circuits.

[j] Shunt trip devices used with remote-mounted ground-fault relaying must operate at 50% of the nominal voltage ratings.

[k] The devices utilizing standard auxiliary relays for control may not function at lower extremes of voltage ranges when relay coils are hot, as after repeated or continuous operation.

[l] Closing functions include (a) the closing power mechanism, and (b) the means (coils, contactors, seal-in relays, and the like) to actuate the power mechanisms. Auxiliary functions include all functions except closing and opening.

[m] Tripping functions are those electrical functions performed intentionally to release the stored energy mechanism allowing the device to separate its primary contacts.
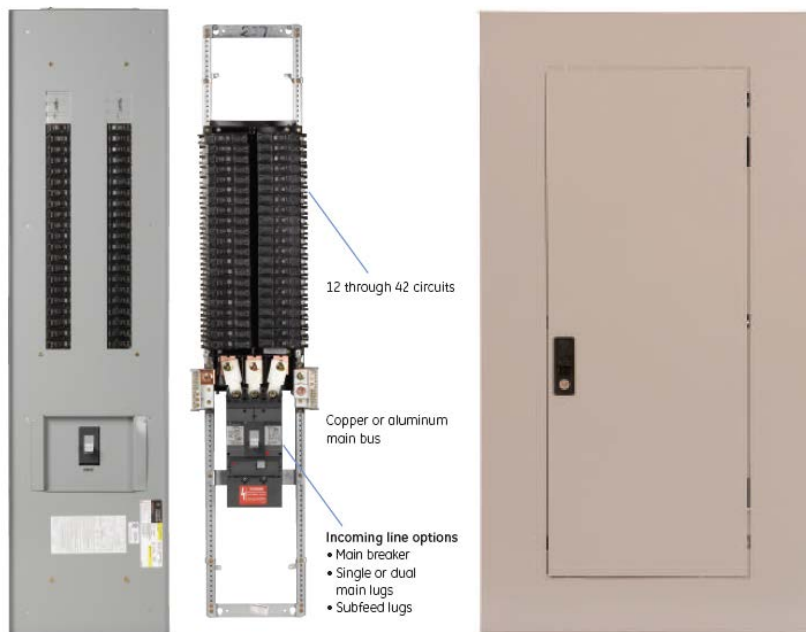
6. Panelboards

While large loads can be supplied directly from switchgear and switchboards, oftentimes another level of disconnects are desired for supplying small and moderate sized loads. Panelboards are often employed either as an intermediate distribution point or as the location of the branch circuit disconnects for the load, although branch circuits for motor loads may be better served using a motor control center. The NRTL listing standard for panelboards is UL 67.

All panelboards are intended for wall mounting; they are not provided in a free standing enclosure (which would then be a switchboard). A structural framework or assembly of struts can be used to support the panelboard if a wall structure is not available for support.

Panelboards are provided in three parts. A box encloses the rear, sides, top, and bottom. The assembly of busses, insulating structure, and connected circuit breakers or switches is referred to as the interior, which is provided with a matching deadfront that consists of grounded sheet steel, is placed in front of the interior. Rectangular openings are provided in the deadfront to allow access to circuit breaker operating handles. The third piece is an outer cover with a hinged door which may be key-locked for security. The outer cover outline will exactly match the outline dimensions of the box for surface mount applications, or it will extend beyond the box outline some amount when the panel is flush mounted in a wall.

Boxes are frequently stocked by distributors and can be shipped prior to the interior and deadfront shipping from the factory. This allows the installer to be able to fully install the conduit system prior to the arrival of the panel interiors.

Panelboards are designed for minimizing space requirements so optional devices and functions that extend beyond basic switching and overcurrent protection may be very limited. The manufacturer should be contacted to determine what special functionality, if any, is available in addition to the circuit breakers or fusible switches to be provided in the panel.

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Figure 12 —The deadfront, interior assembly, and front cover of a lighting panelboard

6.1 Classifications

Commonly available classifications for panelboards used in industrial and commercial applications are (1) distribution panelboards and (2) lighting or branch panelboards. Of the latter, there can be special purpose branch panelboards for column or other narrow width applications and lighting control panelboards. Branch panelboards used in residential applications are referred to as "load centers" and are outside the scope of this standard.

6.1.1 Distribution panelboards

Distribution panelboards are applied when several feeder or branch circuits are rated greater than 100 A, and less than 1200A.

6.1.2 Branch panelboards

Branch panelboards are applied when branch circuits are rated 100 A or less. The branch panel design may have limited room for larger circuit breakers referred to as "subfeeders" in ratings up to 225A.

6.1.2.1 Column panelboards

Column panelboards are designed to fit very narrow spaces. The panelboard will have only one branch circuit per row rather than two per row as in a conventional branch panel.

6.1.2.2 Lighting control panelboards

Lighting control panelboards are branch panels that have specially designed branch breakers that can be electrically opened and closed independent of the tripping mechanism. These panels also contain a lighting controller that can operate a lighting control scheme autonomously, or it can be connected to a larger building automation system. These panelboards replace lighting control schemes where a conventional branch panel is wired to another panel containing lighting contactors. The combination of these two functions into the single panel saves space and reduces installation cost.

The special circuit breakers operated by the control will have additional indicators to show whether they are open or closed, since the toggle handle will remain in the closed position unless the breaker is tripped manually or by an overcurrent condition. Conventional circuit breakers can be intermixed with the special circuit breakers when it is necessary to supply branch circuits that do not need to be operated by the control.

6.2 Ratings

Main current ratings for distribution panels are generally 400 A, 800 A, 1000 A, and 1200 A. Main current ratings for branch panels are generally 100 A (main breaker type), 125 A (main lug only type), 225 A, 400, 600 A, and 800 A. Main current ratings for column panels are generally 100 A (main breaker type), 125 A (main lug only type), and 225 A.

Panelboard designs for common three-phase and single-phase standard voltages are available up to a maximum of 600 Vac. DC ratings are also available.

The short-circuit rating of a panel is determined by the short-circuit rating of the lowest rated component within that panel. Short-circuit ratings are in symmetrical amperes and based on a minimum short-circuit duration of 3 cycles (0.05 s at 60 Hz). Panelboards are short-circuit tested per procedures and criteria listed in UL 67.

A panelboard is fully rated when the lowest short-circuit rated device exceeds the available short-circuit current at the incoming terminals of the panel. Branch circuit breakers may not necessarily be available in the short-circuit ratings required for a given application. However, a series combination rating can be applied to a panel where the branch breaker has been short-circuit tested in combination with a larger breaker that is located either at the panelboard main or somewhere on the supply side of the panel. The series rated panel can be a very cost effective way to apply a panel in a high short-circuit application. Series combination ratings must be determined by test because the dynamic nature of a circuit breaker while it operates on a short-circuit cannot be easily converted to an equation that allows the suitability of a series rating to be determined without test. New panelboards are provided with documentation that lists all the valid series rating combinations allowed for that panel. It should be noted that a fully rated panel does not necessarily have any better selective coordination performance than a series rated panel. For further information on series ratings, refer to IEEE Std 1015™-2006 [B40].

7. Busways

7.1 Origin

Busways originated as a result of a request of the automotive industry in Detroit in the late 1920s for an overhead wiring system that would simplify electrical connections for electric motor-driven machines and permit a convenient arrangement of these machines in production lines. From this beginning, busways have

grown to become an integral part of the low-voltage distribution system for industrial plants at 600 V and below.

Busways are particularly advantageous when numerous current taps are required. Plug-in devices with circuit breakers or fusible switches may be installed and wired without de-energizing the busway if so labeled by the manufacturer.

Power circuits over 600 A are usually more economical and require less space with busways than with conduit and wire. Busways may be dismantled and reinstalled in whole or in part to accommodate changes in the electrical distribution system layout.

7.2 Busway construction

Originally a busway consisted of bare copper conductors supported on inorganic insulators, such as porcelain, mounted within a non-ventilated steel housing. This type of construction was adequate for the current ratings of 225 A through 600 A then used. As the use of busways expanded and increased loads demanded higher current ratings, the housing was ventilated to provide better cooling at higher capacities. The bus bars were covered with insulation for safety and to permit closer spacing of bars of opposite polarity in order to achieve lower reactance and voltage drop.

In the late 1950s, busways were introduced utilizing conduction for heat transfer by placing the insulated conductor in thermal contact with the enclosure. By utilizing conduction, current densities are achieved for totally enclosed busways that are comparable to those previously attained with ventilated busways. Totally enclosed busways of this type have the same current rating regardless of mounting position. Bus configuration may be a stack of one bus bar per phase (0 A through 800 A), and higher ratings will use two (3000 A) or three stacks (5000 A). Each stack may contain all three phases, neutral, and grounding conductor to minimize circuit reactance (See Figure 13).

Early busway designs required multiple nuts, bolts, and washers to electrically join adjacent sections. Present designs use a single bolt for each stack. Joint connection hardware is captive to the busway section when shipped from the factory. Installation labor is greatly reduced with corresponding savings in installation costs.

Busway conductors and current-carrying parts can be either copper or aluminum or copper alloy rated for the purpose. Compared to copper, electrical grade aluminum has lower conductivity (the minimum for aluminum is 55%; for copper, 97%) and less mechanical strength. Generally, for equal current-carrying ability, aluminum is lighter in weight and less costly.

To prevent oxides or insulating film on the surfaces, all contact locations on current-carrying parts are plated with tin or silver (the exception being copper conductors in lighting busways and trolley busways). Power and distribution busways use Belleville springs (concave washers) and bolting practices at the joints to maintain mechanical integrity.

Busway supplied for North American applications is usually manufactured in 10-ft sections. Since the busway must conform to the building structure, all possible combinations of elbows, tees, and crosses are available. Feed and tap fittings to other electric equipment, such as switchboards, transformers, motor-control centers, etc., are available. Plugs for plug-in busway use fusible switches and/or molded-case circuit breakers to protect the feeder or branch circuit. Neutral conductors may be supplied if required.

Four types of busways are available, complete with fittings and accessories, providing a unified and continuous system of enclosed conductors (Figure 14):

a)   Feeder busway for low-impedance and minimum voltage drop for distribution of power as needed;

b) Plug-in busway for easy connection or re-arrangement of loads;

c) Lighting busway to provide electric power and mechanical support for lighting or small loads;

d) Trolley busway for mobile power tapoffs to electric hoists, cranes, portable tools, etc.
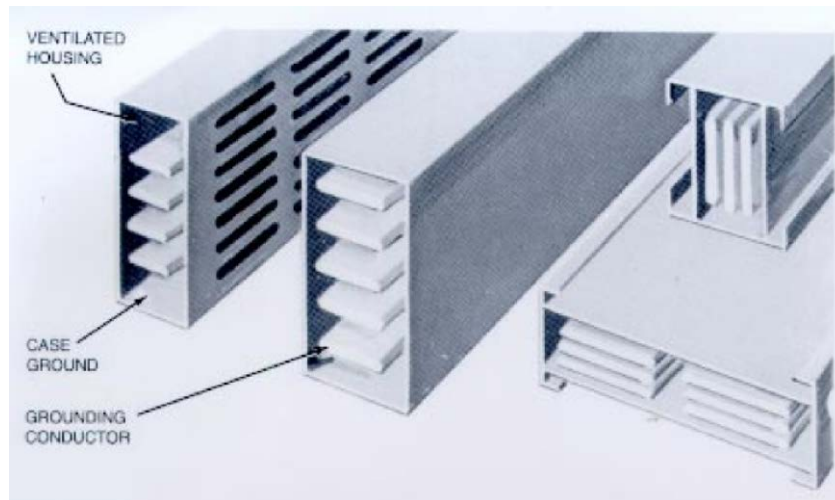
Figure 13 — Typical busway construction
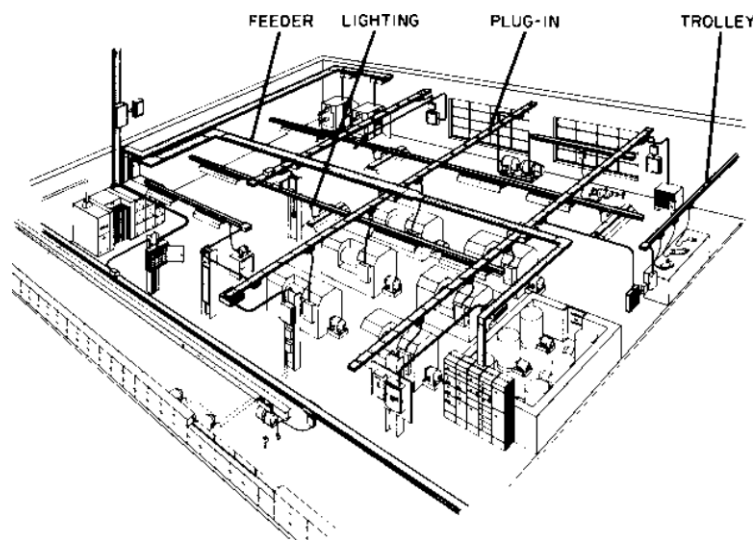
**Figure 14 — Illustration of versatility of busways, showing use
of feeder, plug-in, lighting, and trolley types**

7.3 Feeder busway

Feeder busway is used to transmit large blocks of power. It has a very low and balanced circuit reactance to minimize voltage drop and sustain voltage at the utilization equipment (Figure 15).

Feeder busway is frequently used between the source of power, such as a distribution transformer or service drop, and the service entrance equipment. Industrial plants use feeder busway from the service equipment to supply large loads directly and to supply smaller current ratings of feeder and plug-in busway, which in turn supply loads through power take-offs or plug-in units.

Available current ratings range from 600 A to 5000 A, 600 Vac or Vdc. By paralleling runs, higher ratings can be achieved. The manufacturer should be consulted for dc ratings. Feeder busway is available in single-phase and three-phase service with 50% and 100% neutral conductor. A grounding bus is available with all ratings and types. Available short-circuit current ratings are 42 000 A to 200 000 A, symmetrical rms (see 7.8.2). The voltage drop of low-impedance feeder busway with the entire load at the end of the run ranges from 6 V to 12 V/100 m (1 V to 3 V/100 ft), line-to-line, depending upon the type of construction and the current rating (see 7.8.3).

Feeder busway is available in indoor and outdoor construction. Outdoor construction is designed so that exposure to the weather will not interfere with successful operation (see NEMA BU 1-2002). Outdoor busway also can be used for indoor applications where similar adverse conditions might prevail. No busway is suitable for immersion in water or to be solidly entrenched.
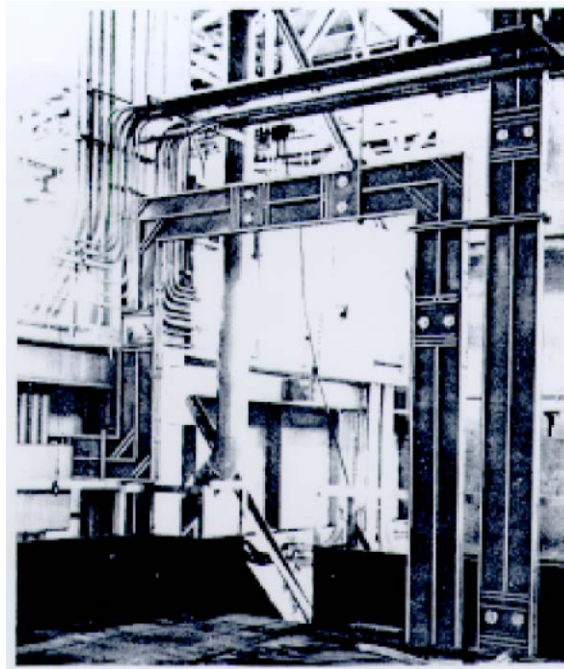

Figure 15 —Feeder busway

7.4 Plug-in busway

Plug-in busway is used in industrial plants as an overhead system to supply power to utilization equipment. Plug-in busway provides tapoff provisions at regular intervals, approximately every 0.6 m (2 ft), over the length of the run for connection of a switch or circuit breaker to the busway. Load side cable connections can then be short and direct.

Plug-in tapoffs (bus plugs) can be connected to their loads by conduit and wire or flexible bus drop cable. Bus plugs can be removed, relocated, and reused. The use of flexible cable permits the bus plug and machine it serves to be relocated and put back into service in a minimum of time (see Figure 16).

Bus plugs are available in several types. They include fusible switches, circuit breakers, static voltage protectors (potentializer), ground detectors (indicating), combination motor starters and lighting contactors, transformers, and capacitor plugs. Many can be equipped with additional accessories, such as control power transformers, relays, indicating lights (blown fuse), and terminal blocks for remote control and indication.

Busway is totally enclosed and can be of the ventilated or non-ventilated design. Plug-in busways have current ratings ranging from 100 A to 5000 A. Plug-in and feeder busway sections of the same manufacturers above 600 A are usually of compatible design and can be interchangeable, allowing for a section of plug-in to be installed in a feeder run where tapoffs are desired. Bus plugs are generally limited to maximum ratings of 800 A for fused-switch type plugs and 1200 A for circuit breaker type plugs.

Short-circuit current ratings vary from 10 000 A to 200 000 A symmetrical rms (see 7.8.2). The voltage drop ranges are approximately from 6 V to 12 V/100 m (1V to 3 V/100 ft), line-to-line, for evenly distributed loading. If the entire load is concentrated at the end of the run, these values double (see 7.8.3).

A neutral bar may be provided for single-phase loads such as lighting. Neutral bars usually are of the same capacity as the phase bars.
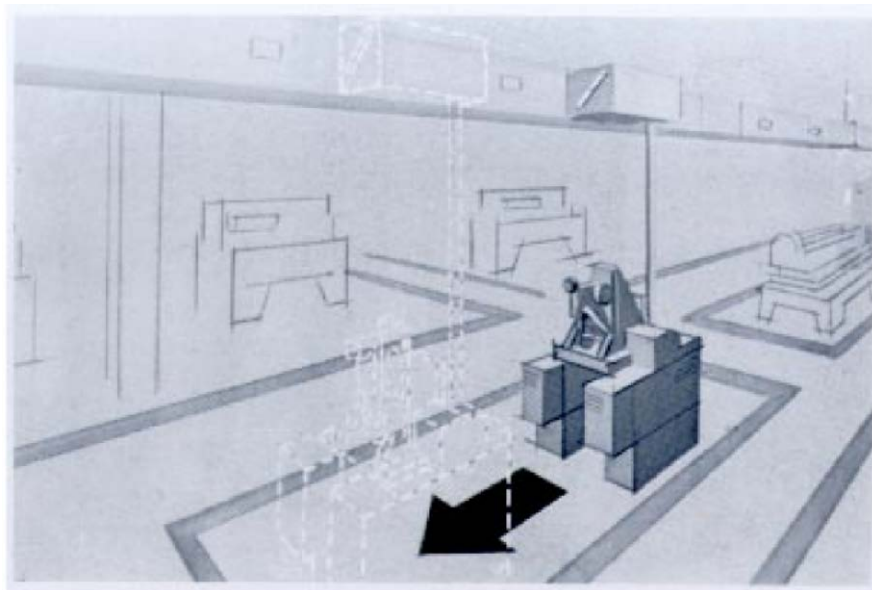
Figure 16 —Machine installation using a busway feeder

The bus housing may be used as an equipment grounding path. However, grounding bus bar is often added for greater system protection and coordination under ground-fault conditions. The grounding bus bar provides a low-impedance ground path and reduces the possibility of arcing at the joint under high-level ground faults if the housing is used as a ground path. (See 7.8.2 for additional details.)

7.5 Lighting busway

Lighting busway is rated a maximum of 60 A, 300 V-to-ground, with two, three, or four conductors. It may be used on 480 Y/277 V or 208 Y/120 V systems and is specifically designed for use with fluorescent and high-intensity discharge lighting (Figure 17).

Tapoffs for lighting busway are available in various types and include those with built-in circuit protection by either fuse or circuit breaker. Accessories include special mounting brackets and tapoffs for surface or close coupling attachment of fluorescent lighting fixtures to the busway. Lighting busway can be surface-mounted, recessed in dropped ceilings, or suspended from drop rods. Hangers are available to accommodate each method.

Lighting busways provide power to the lighting fixture and serve as the mechanical support for the fixture. Auxiliary supporting means called strength beams are available for increasing supporting intervals. The strength beams provide supports for the lighting busway as required by the NEC®. Lighting busway is also used to provide power for light industrial applications.

Figure 17 —Example of lighting busway

7.6 Trolley busway

Trolley busway is constructed to receive stationary or movable take-off devices to power overhead cranes, monorail systems, industrial doors, and conveyor lines. Trolley busways are not suitable for outdoor application. They are used on a moving production line to supply electric power to a motor or a portable tool moving with a production line, or where operators move back and forth to perform their specific operations.

Trolley busway is available in current ratings ranging from 60 A to 800 A, up to 600 V ac or dc, and 3 wire, 4 wire, and 5 wire. The steel casing serves as the ground. Tapoffs (moving trolleys) range from 15 A to 200 A and can be equipped with circuit breakers, fusible protection, starters, contactors, and relays. Depending on manufacturer's recommendations, trolleys can support hanging loads of up to 30 lbs. Both horizontal and vertical curves are available, as well as isolation sections, end ramps, and switching sections.

7.7 Standards

Busways installation, application, and design conform to the following standards:

— UL 857-2011

— NEMA BU 1-2002

UL 857-2011 and NEMA BU1-2002 are primarily manufacturing and testing standards. The NEMA standard is generally an extension of the UL standard to areas that UL does not cover. The most important areas are busway physical parameters, resistance R, reactance X, and impedance Z, and short-circuit testing and rating.

Article 368 of the NEC® deals primarily with criteria for busway installation. Some of its most important areas are as follows:

— Busway may be installed only where located in the open and visible. Installation behind panels is permitted if certain defined conditions are met. Refer to the NEC®.

— Busway may not be installed where subject to physical damage, corrosive vapors, or in hoistways.

— When specifically approved for the purpose, busway may be installed in a hazardous (classified) location, outdoors, or in wet or damp locations.

— Busway must be supported at intervals not to exceed 5 ft unless otherwise approved. Where specifically approved for the purpose, horizontal busway may be supported at intervals up to 10 ft, and vertical busway may be supported at intervals up to 16 ft.

— Busway must be totally enclosed (non-ventilated) where passing through floors and for a minimum distance of 6 ft above the floor to help provide protection from physical damage. It may extend through walls if joints are outside the walls.

State and local electrical codes may have specific requirements over and above UL 857-2011 and the NEC®. Appropriate code authorities and manufacturers should be contacted to ensure that requirements are met.

7.8 Selection and application of busways

To apply busway properly in an electric power distribution system, some of the more important items to consider are the following listed in 7.8.1 through 7.8.6.

7.8.1 Current-carrying capacity

Busway should be rated on a temperature-rise basis to help provide safe operation, long life, and reliable service.

Conductor size (cross-sectional area) should not be used as the sole criterion for specifying busway. Busway may have seemingly adequate cross-sectional area yet have a dangerously high temperature rise. The UL requirement for temperature rise (55 °C) (see UL 857-2011) should be used to specify the maximum temperature rise permitted. Larger cross-sectional areas can be used to provide lower voltage drop and temperature rise.

Although the temperature rise will not vary significantly with changes in ambient temperature, it may be a significant factor in the life of the busway. The limiting factor in most busway designs is the insulation life, and there is a wide range of types of insulating materials used by various manufacturers. If the ambient temperature exceeds 40 °C or a total temperature in excess of 95 °C is expected, then the manufacturer should be consulted.

7.8.2 Short-circuit current rating

The bus bars in busway may be subject to electromagnetic forces of considerable magnitude by a short-circuit current. The generated force per unit length of bus bar is directly proportional to the square of the short-circuit current and is inversely proportional to the spacing between bus bars. Short-circuit current ratings are generally assigned in accordance with NEMA BU1-2002 and tested in accordance with UL 857-2011. The ratings are based on (1) the use of an adequately rated protective device ahead of the busway that will clear the short-circuit in 3 cycles and (2) application in a system with short-circuit power factor not less than that given in Table 8.

If the system on which the busway is to be applied has a lower short-circuit power factor (larger X/R ratio), the short-circuit current rating of the bus may have to be increased. The manufacturer should then be consulted.

The required short-circuit current rating should be determined by calculating the available short-circuit current and X/R ratio at the point where the input end of the busway is to be connected. The short-circuit current rating of the busway must equal or exceed the available short-circuit current.

The short-circuit current may be reduced by using a current-limiting fuse or circuit breaker at the supply end of the busway to cut it off before it reaches maximum value [see IEEE Std 141™-1993 (*IEEE Red Book™*), Chapter 5].

Short-circuit current ratings are dependent on many factors, such as bus bar center line spacing, size, strength of bus bars, and mechanical supports.

Since the ratings are different for each design of busway, the manufacturer should be consulted for specific ratings. Short-circuit current ratings should include the ability of the ground return path (housing and ground bar if provided) to carry the rated short-circuit current. Failure of the ground return path to adequately carry this current can result in arcing at joints, creating a fire hazard. The ground-fault current can also be reduced to the point that the overcurrent protective device does not operate. Bus plugs and attachment accessories also should have adequate short-circuit interrupting and/or withstand ratings.

Table 8—Busway ratings as a function of short-circuit power factor

Busway rating (symmetrical rms amperes)	Power factor	X/R ratio[a]
10 000 or less	0.50	1.7
10 001 to 20 000	0.30	3.2
Above 20 000	0.20	4.9

[a]X/R is load reactance X divided by load resistance R.

7.8.3 Voltage drop

Line-to-neutral voltage drop V in busway may be calculated by the following formulas. The exact formulas for concentrated loads at the end of the line are, with V_R known,

$$V_D = \sqrt{(V_R \cos\phi + IR)^2 + (V_R \sin\phi + IX)^2} - V_R \qquad (2)$$

and with V_S known,

$$V_D = V_S + IR \cos\phi + IX \sin\phi - \sqrt{V_S^2 - (IX \cos\phi - IR \sin\phi)^2} \qquad (3)$$

where

$$V_R = \frac{Z_L}{Z_S}, \quad V_D = V_S - V_R \tag{4}$$

Multiply the line-to-neutral voltage drop by √3 to obtain the line-to-line voltage drop in three-phase systems. Multiply the line-to-neutral voltage drop by 2 to obtain the line-to-line voltage drop in single-phase systems.

The approximate formulas for concentrated loads at the end of the line are as follows:

$$VD = I(R\cos\phi + X\sin\phi) \tag{5}$$

$$V_{pr} = \frac{S(R\cos\phi + X\sin\phi)}{10V_k^2} \tag{6}$$

The approximate formula for distributed load on a line is as follows:

$$V_{pr} = \frac{S(R\cos\phi + X\sin\phi)}{10V_k^2}\left(1 - \frac{L_1}{2L}\right) \tag{7}$$

where

V_D	is the voltage drop, in volts
V_{pr}	is the voltage drop, in percent of voltage at sending end
V_S	is the line-to-neutral voltage at sending end, in volts
V_R	is the line-to-neutral voltage at receiving end, in volts
ϕ	is the angle whose cosine is the load power factor
R	is the resistance of circuit, in ohms per phase
X	is the reactance of circuit, in ohms per phase
I	is the load current, in amperes
Z_L	is the load impedance, in ohms
Z_S	is the circuit impedance, in ohms, plus load impedance, in ohms, added vectorially
S	is the three-phase apparent power for three-phase circuits or single-phase apparent power for single-phase circuits, in kilovoltamperes
V_k	is the line-to-line voltage, in kilovolts
L_1	is the distance from source to desired point, in feet
L	is the total length of line, in feet

The foregoing formulas for concentrated loads may be verified by a trigonometric analysis of Figure 18. From this figure it can be seen that the approximate formulas are sufficiently accurate for practical purposes. In practical cases, the angle between V_R and V_S will be small (much smaller than in Figure 18, which has been exaggerated for illustrative purposes). The error in the approximate formulas diminishes as the angle between V_R and V_S decreases and is zero if that angle is zero. This latter condition will exist when the X/R ratio (or power factor) of the load is equal to the X/R ratio (or power factor) of the circuit through which the load current is flowing.

In actual practice, loads may be concentrated at various locations along the feeders, uniformly distributed along the feeder, or any combination of the same. A comparison of the approximate formulas for concentrated end loading and uniform loading will show that a uniformly loaded line will exhibit one-half the voltage drop as that due to the same total load concentrated at the end of the line. This aspect of the approximate formula is mathematically exact and entails no approximation. Therefore, in calculations of composite loading involving approximately uniformly loaded sections and concentrated loads, the uniformly loaded sections may be treated as end-loaded sections having one-half normal voltage drop of the same total load. Thus, the load can be divided into a number of concentrated loads distributed at various distances along the line. The voltage drop in each section may then be calculated for the load that it carries.

Three-phase voltage drops may be determined with reasonable accuracy by the use of Table 9 and Table 10. These are typical values for the sandwich-type design of busway. The voltage drops will be different for other types of busway and will vary by manufacturer within each type. The voltage drop shown is three-phase, line-to-line, per 100 m (and per 100 V) at rated load on a concentrated loading basis for feeder, plug-in, and trolley busway.
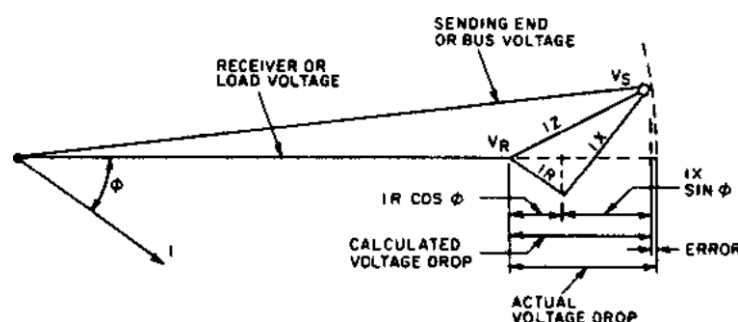
Figure 18 —Diagram illustrating voltage drop and indicating error when approximate voltage-drop formulas are used

Lighting busway values are single-phase, distributed loading. For other loading and distances, use the following formula:

$$\text{voltage drop } V_D = \text{table } V_D \times \frac{\text{actual load}}{\text{rated load}} \times \frac{\text{actual distance (feet)}}{100 \text{ ft}} \tag{8}$$

The voltage drop for a single-phase load connected to a three-phase busway is 15.5% higher than the value shown in the tables. Typical values of resistance and reactance are shown in Table 11. Resistance is shown at normal room temperature (25 °C). This value should be used in calculating the short-circuit current available in systems, since short circuits can occur when busway is lightly loaded or initially energized. To calculate the voltage drop when fully loaded (75 °C), the resistance of copper and aluminum should be multiplied by 1.19.

**Table 9—Voltage-drop values for three-phase sandwiched busways
with copper bus bars, in volts/100 m (volts/100 ft), line-to-line,
at rated current with concentrated load[a]**

Current rating (amperes)	Load power factor (percent, lagging)								
	20	30	40	50	60	70	80	90	100
600	7.02 (2.14)	8.04 (2.45)	8.76 (2.67)	9.38 (2.86)	9.97 (3.04)	10.43 (3.18)	10.76 (3.28)	10.83 (3.30)	9.38 (2.86)
800	7.12 (2.17)	8.10 (2.47)	8.76 (2.67)	9.35 (2.85)	9.84 (3.00)	10.24 (3.12)	10.47 (3.19)	10.40 (3.17)	8.83 (2.69)
1000	6.59 (2.01)	7.61 (2.32)	8.27 (2.52)	8.86 (2.70)	9.35 (2.85)	9.78 (2.98)	10.04 (3.06)	10.04 (3.06)	8.66 (2.64)
1200	5.87 (1.79)	6.89 (2.10)	7.48 (2.28)	8.04 (2.45)	8.50 (2.59)	8.89 (2.71)	9.15 (2.79)	9.15 (2.79)	7.91 (2.41)
1350	6.10 (1.86)	7.02 (2.14)	7.61 (2.32)	8.14 (2.48)	8.60 (2.62)	8.96 (2.73)	9.22 (2.81)	9.22 (2.81)	7.91 (2.41)
1600	6.36 (1.94)	7.09 (2.16)	7.71 (2.35)	8.23 (2.51)	8.66 (2.64)	9.02 (2.75)	9.25 (2.82)	9.19 (2.80)	8.66 (2.64)
2000	6.82 (2.08)	7.32 (2.23)	7.87 (2.40)	8.40 (2.56)	8.83 (2.69)	9.15 (2.79)	9.35 (2.85)	9.28 (2.83)	7.84 (2.39)`
2500	6.07 (1.85)	6.46 (1.97)	6.99 (2.13)	7.41 (2.26)	7.84 (2.39)	8.10 (2.47)	8.30 (2.53)	8.23 (2.51)	6.92 (2.11)
3000	6.43 (1.96)	7.05 (2.15)	7.61 (2.32)	8.07 (2.46)	8.50 (2.59)	8.83 (2.69)	8.99 (2.74)	8.96 (2.73)	7.55 (2.30)
4000	6.10 (1.86)	6.76 (2.06)	7.35 (2.24)	7.84 (2.39)	8.27 (2.52)	8.63 (2.63)	8.83 (2.69)	8.79 (2.68)	7.51 (2.29)
5000	6.07 (1.85)	6.46 (1.97)	6.99 (2.13)	7.41 (2.26)	7.78 (2.37)	8.07 (2.46)	8.23 (2.51)	8.17 (2.49)	6.86 (2.09)
NOTE—These are average values for four major manufacturers of sandwiched busway. Voltage-drop values are based on bus-bar resistance at 75 °C (ambient temperature of 25 °C plus average conductor temperature at full load of 50 °C rise).									

[a]Divide values by 2 for distributed loading.

7.8.4 Thermal expansion

As load is increased, the bus-bar temperature will increase and the bus bars will expand. The lengthwise expansion between no load and full load will range from 4.2 cm/100 m to 8.3 cm/100 m (1/2 in/100 ft to 1 in/100 ft). The amount of expansion will depend on the total load, size, and location of the tapoffs, and the size and duration of varying loads. To accommodate the expansion, the busway should be mounted using hangers that permit it to move. It may be necessary to insert expansion lengths in the busway run. To locate expansion lengths, the method of support, the location of power take-offs, the degree of movement permissible at each end of the run, and the orientation of the busway must be known. The manufacturer can then make recommendations as to the location and number of expansion lengths.

**Table 10 —Voltage-drop values for three-phase sandwiched busways
with aluminum bus bars, in volts/100 m (volts/100 ft), line-to-line,
at rated current with concentrated load[a]**

Current rating (amperes)	Load power factor (percent, lagging)								
	20	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
600	6.27 (1.91)	7.71 (2.35)	8.89 (2.71)	9.68 (2.95)	10.56 (3.22)	11.35 (3.46)	12.04 (3.67)	12.53 (3.82)	11.88 (3.62)
800	6.07 (1.85)	6.99 (2.13)	7.87 (2.40)	8.76 (2.67)	9.55 (2.91)	10.27 (3.13)	10.89 (3.32)	11.35 (3.46)	10.73 (3.27)
1000	5,54 (1.69)	6.89 (2.04)	7.64 (2.33)	8.53 (2.60)	9.38 (2.86)	10.14 (3.09)	10.79 (3.29)	11.32 (3.45)	10.53 (3.21)
1200	5.61 (1.71)	6.66 (2.03)	7.58 (2.31)	8.43 (2.57)	9.22 (2.81)	9.97 (3.04)	10.60 (3.23)	11.06 (3.37)	10.53 (3.21)
1350	5.15 (1.57)	5.97 (1.82)	6.82 (2.08)	7.58 (2.31)	8.30 (2.53)	8.99 (2.74)	9.55 (2.91)	9.97 (3.04)	9.51 (2.90)
1600	5.61 (1.71)	6.40 (1.95)	7.22 (2.20)	7.97 (2.43)	8.69 (2.65)	9.32 (2.84)	9.84 (3.00)	10.20 (3.11)	9.61 (2.93)
2000	5.68 (1.73)	6.43 (1.96)	7.22 (2.20)	7.97 (2.43)	8.66 (2.64)	9.28 (2.83)	9.81 (2.99)	10.14 (3.09)	9.45 (2.88)
2500	5.48 (1.67)	6.43 (1.96)	7.25 (2.21)	8.04 (2.45)	8.73 (2.66)	9.35 (2.85)	9.88 (3.01)	10.24 (3.12)	9.58 (2.92)
3000	5.35 (1.63)	6.30 (1.92)	7.09 (2.16)	7.84 (2.39)	8.53 (2.60)	9.15 (2.79)	9.68 (2.95)	10.01 (3.05)	9.38 (2.86)
4000	5.71 (1.74)	6.36 (1.94)	7.15 (2.18)	7.84 (2.39)	8.53 (2.60)	9.09 (2.77)	9.51 (2.90)	9.84 (3.00)	9.12 (2.78)

NOTE—These are average values for four major manufacturers of sandwiched busway. Voltage-drop values are based on bus-bar resistance at 75 °C (ambient temperature of 25 °C plus average conductor temperature at full load of 50 °C rise).

[a]Divide values by 2 for distributed loading.

Table 11 —Typical busway parameters, line-to-neutral, in mΩ/100 ft, 60 Hz, 25 °C

Current rating (amperes)	Aluminum		Copper	
	R	**X**	**R**	**X**
600	2.982	1.28	2.33	1.57
800	2.00	0.80	1.63	1.25
1000	1.60	0.64	1.27	0.92
1200	1.29	0.55	0.97	0.69
1350	1.03	0.44	0.86	0.63
1600	0.89	0.38	0.72	0.55
2000	0.70	0.32	0.58	0.46
2500	0.57	0.26	0.41	0.32
3000	0.46	0.21	0.37	0.29
4000	0.34	0.16	0.28	0.21
5000	—	—	0.20	0.16

NOTE—Resistance values increase as temperature increases. Reactance values are not affected by temperature. The above values are based on conductor temperature of 25 °C (normal room temperature) since short-circuits may occur when busway is initially energized or lightly loaded. To convert values to fully loaded (75 °C), multiply resistance of copper or aluminum by 1.19.

7.8.5 Building expansion joints

Busway, when crossing a building expansion joint, must include provision for accommodating movement of the building structure. Fittings providing for up to 7.62 cm (3 in) of movement are available.

7.8.6 Welding loads

The busway and the plug-in device must be properly sized when plug-in busway is used to supply power to welding loads. The plug sliding contacts (stabs) and protective device (circuit breaker or fused switch) should have sufficient rating to carry both the continuous and peak welding load. This is normally done by determining the equivalent continuous current of the welder based on the maximum peak welder current, the duration of the welder current, and the duty cycle. Values may be obtained from the welder manufacturer. Loads 600 A and greater require special attention including consideration of bolted taps.

7.9 Layout

Busway must be tailored to the building in which it is installed. Once the basic engineering work has been completed and the busway type, current rating, number of poles, etc., are determined, a layout should be made for all but the simplest straight runs. The initial step in the layout is to identify and locate the building structure (walls, ceilings, columns, etc.) and other equipment that is in the busway route. A layout of the busway to conform to this route is made. Although the preliminary layout (drawings for approval) can be made from architectural drawings, it is essential that field measurements be taken to verify building and busway dimensions prior to the release of the busway for manufacture. Where dimensions are critical, it is recommended that a section be held for field check of dimensions and manufactured after the remainder of the run has been installed. Manufacturers will provide quick delivery on limited numbers of these field-check sections.

Busway has great physical and electrical flexibility. It may be tailored to almost any layout requirement. However, some users find it a good practice to limit their busway installations to a minimum number of current ratings and maintain as many 10 ft lengths as possible. This enables them to reuse the busway components to maximum advantage where production line changes, etc., require relocation of the busway.

Another important consideration when laying out busway is coordination with other trades. Since there is a finite time lapse between job measurement and actual installation, other trades may use the busway clear area if coordination is lacking. Again, standard components such as elbows, tees, offsets, and cable tap boxes can help since they are more readily available (sometimes from stock). By reducing the time between final measurement and installation, in addition to proper coordination, the chances of interference from other trades can be reduced to a minimum.

Finally, terminations are a significant part of busway layout considerations. For ratings 600 A and above, direct-bused connections to the switchboard, motor-control center, etc., can reduce installation time and problems. For ratings up to 600 A, direct-bused terminations are generally not practical or economical. These lower current ratings of busway are usually fed by short cable runs.

7.10 Installation

Busway installs quickly and easily. When compared with other distribution methods, the reduced installation time for busway can result in direct savings on installation costs. In order to help ensure safety, reliability, and long life from a busway system, proper installation is a must. The guidelines below can serve as an outline from which to develop a complete installation procedure and timetable. NEMA BU 1.1-2010 should also be consulted for recommendations on the installation, handling, and operation of low-voltage busway.

7.10.1 Procedure prior to installation

a) Manufacturers supply installation drawings on all but the simplest of busway layouts. Study these drawings carefully. Where drawings are not supplied, make your own.

b) Verify actual components on hand against those shown on installation drawing to be sure that there are no missing items. Drawings identify components by catalog number and location in the installation. Catalog numbers appear on section nameplate and carton label. Location on the installation (item number) will also be on each section.

c) During storage (prior to installation) all components, even the weatherproof type, should be stored in a clean, dry area and protected from physical damage.

d) Always read manufacturer's instructions for installation of individual components. If you are still in doubt, ask for more information—never guess.

e) Electrical testing of individual components prior to installation should be done. Identification of defective pieces prior to installation will save considerable time and money.

f) Finally, pre-position hanger supports (drop rods, etc.) and hangers of the type that can be pre-positioned. Lateral bracing should be provided to minimize sway. The actual installation of busway components can now begin.

7.10.2 Procedure during installation

> **WARNING**
>
> Safety is most important during the installation procedure and should be foremost in the installer's mind at all times. Deviating from prescribed or written safety policies can result in human injury, including death as well as equipment damage. If safety is in doubt at any time, do not proceed with the installation until all concerns are satisfied.

a) Almost all busway components are built with two dissimilar ends that are commonly called bolt end and slot end. Refer to the installation drawing to properly orient the bolt and slot ends of each component. This is important because it is not possible to properly connect two slot ends or bolt ends.

b) Lift individual components into position and attach to hangers. It is generally best to begin this process at the end of the busway run that is most rigidly fixed (i.e., the switchboards).

c) To ensure proper phasing, pay particular attention to "TOP" labels and other orientation marks where applicable.

d) As each new component is installed in position, tighten the joint bolt to proper torque per manufacturer's instructions. Also install any additional joint hardware that may be required.

e) On plug-in busway installations, attach plug-in units in accordance with manufacturer's instructions and proceed with wiring.

f) Safety at this procedure of the installation is paramount. As noted at the beginning of the chapter, bus plugs equipped with one set of plug-in fingers or stabs may be installed while the busway is energized. In general, that includes bus plugs up to a nameplate current rating of 400 A. It should be noted, however, that 200 A and 400 A bus plugs are heavy, large devices, not easily handled or installed by one person. Bus plugs rated 200 A and below generally do not require independent support means other than the busway. To install or remove bus plugs rated 600 A and higher, it is required that the busway be de-energized. Ratings of these sizes are equipped with two or more sets of plug-in fingers or have clamp-type bolted connections for direct attachment to the busway phase bars. All bus plugs constructed accordingly will have attached NEMA warning instructions in accordance with NEMA BU 1-2002, which states, "Turn off power to busway before installing, removing, or working on this equipment."

g) Outdoor busway may require removal of weep-hole screws and addition of joint shields. Pay particular attention to installation instructions to ensure that all steps are followed.

7.10.3 Procedure after installation

Be sure to recheck all steps to ensure that you have not forgotten anything. Be particularly sure that all joint bolts have been properly tightened. At this point the busway installation should be almost complete. Before energizing, however, the complete installation should be properly tested.

7.11 Field testing

The completely installed busway run should be electrically tested prior to being energized. The testing procedure should first verify that the proper phase relationships exist between the busway and associated equipment. This phasing and continuity test can be performed in the same manner as similar tests on other pieces of electric equipment on the job.

All busway installations should be tested with a megohmmeter or high-potential voltage to be sure that excessive leakage paths between phases and ground do not exist. Megohmmeter values depend on the busway construction, type of insulation, size and length of busway, and atmospheric conditions. Acceptable values for a particular busway should be obtained from the manufacturer. Minimum megohm readings should be no less than 100 divided by the length of the run in feet.

If a megohmmeter is used, it should be rated 1000 V direct current. Normal high-potential test voltages are twice rated voltage plus 1000 V for 1 min. Since this may be above the corona-starting voltage of some busway, frequent testing is undesirable. A common testing method currently used is to periodically conduct a thermographic survey of the busway installation.

7.12 Busways over 600 V (metal-enclosed bus)

Busway over 600 V is referred to as metal-enclosed bus and consists of three types: isolated phase, segregated phase, and non-segregated phase. Isolated phase and segregated phase are utility-type busways used in power generation stations. Industrial plants outside of power generation areas use non-segregated phase for connection of transformers and switchgear and interconnection of switchgear lineups. The advantage of metal-enclosed bus over cable is a simpler connection to equipment (no potheads or stress-relieving terminations required). It is rarely used to feed individual loads.

7.12.1 Standards

The NEC® requires that the metal-enclosed bus nameplate specify its rated:

- a)   Voltage
- b)   Continuous current
- c)   Frequency
- d)   Impulse withstand voltage
- e)   60 Hz withstand voltage
- f)   Momentary current
- g)   Manufacturer's name or trademark

The NEC® provides a fine print note (for informational purposes only) that states, "See ANSI C37.23-1987 (Reaff 1991), Guide for Metal-Enclosed Bus and Calculating Losses in Isolated Phase Bus, for Construction and Testing Requirements for Metal-enclosed Buses."

7.12.2 Ratings

Table 12 specifies the voltage, insulation, and the continuous and momentary-current levels for metal-enclosed bus. The ratings are equal to the corresponding values for metal-enclosed switchgear.

Table 12 —Voltage, insulation, continuous-current, and momentary-current ratings of non-segregated-phase metal-enclosed bus

Voltage (kV rms)		Continuous current (A)	Insulation, withstand level (kV)			Momentary current (kA, rms asymmetrical)
Nominal	Rated maximum		Power frequency (rms), 1 min	DC withstand, 1 min[4]	Impulse	
4.16	4.76	[1]	19.0	27.0	60	49 to 98
13.8	15.00	[2]	36.0	50.0	95	31 to 98
23.0	27.00	[3]	60.0	—	125	25 to 39
34.5	38.00	[4]	80.0	—	150	25 to 62
NOTE—High-potential testing is 75% of power frequency voltages.						

Source: Based on IEEE Std C37.23™-2003.

[1] (1200, 2000, 3000, 4000, 5000, 6000)

[2] (1200, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500, 6000)

[3] (1200, 2000, 2500, 3000)

[4] The presence of "dc withstand dry" does not imply any requirement for a dc withstand test on either ac or dc equipment. This column is given as a reference only for those using dc tests and represents values believed to be appropriate and approximately equivalent to the corresponding ac power frequency withstand test values specified for each class of bus.

Because of the variable voltage distribution encountered when making dc withstand tests and variances in leakage currents associated with various insulation systems, the manufacturer should be contacted for recommendations before applying dc withstand tests to this equipment.

Continuous-current ratings are based on a maximum temperature rise of 65 °C of the bus (30 °C if joints are not electroplated). Insulation temperature limits vary with the class of insulating material. Maximum total temperature limits for metal-enclosed bus are based on 40 °C ambient. If the ambient temperature will exceed 40 °C, the manufacturer should be consulted.

The momentary-current rating is the maximum rms total current (including direct-current component) that the metal-enclosed bus can carry without electrical, thermal, or mechanical damage. The momentary current rating is established by a test that has a duration of 10 cycles, unless limited to a shorter time by the protective device.

7.12.3 Construction

Metal-enclosed (non-segregated phase) bus consists of aluminum or copper conductors with bus supports usually of glass polyester or porcelain. Bus bars are insulated with sleeves or by fluid bed process. After installation, joints are covered with boots or tape. Metal-enclosed bus is totally enclosed. The enclosure is

fabricated from steel in lower continuous-current ratings and aluminum or stainless steel in higher ratings. Normal lengths are 8 ft to 10 ft with a cross section of approximately 16 in by 26 in to 36 in, depending on conductor size and spacing. Electrical connection points are electroplated with either silver or tin. Indoor and outdoor (weatherproof) constructions are available. Space heaters should be provided where condensation is a concern.

7.12.4 Field testing

After installation, the metal-enclosed bus should be electrically tested prior to being energized. Phasing and continuity tests can be performed with other associated electric equipment on the job. Megohmmeter tests can be made similar to those described for busway under 600 V. High-potential tests should be conducted at 75% of the values shown in the "Power frequency (rms), 1 min" ratings column of Table 12.

8. Transformers

8.1 General

Transformers are devices that use the principle of magnetic induction to transfer the energy delivered in an ac current from one voltage level to another. Transformers made possible the ability to deliver large amounts of electrical power over long distances, and allowed power generator sources to be located away from the loads that required their power. Since it is more economical for large industrial and commercial facilities to receive their power at the distribution or even transmission voltages used by utilities, the transformer becomes critical to the industrial or commercial power system for converting the power received from the utility to a voltage that can be used most safely and effectively by the load equipment.

Transformers provide the capability to:

    a)   Step-down voltage from a supply voltage to a utilization voltage

    b)   Step-up voltage from a lower to a higher distribution voltage

    c)   Reduce harmonic currents drawn from the distribution system

    d)   Insert impedance into a system to reduce short-circuit currents

    e)   Isolate loads from certain transient noise

    f)   Convert an ungrounded system to a grounded system

8.2 Transformer construction

Transformer cores are manufactured of varnished laminations of steel alloyed with silicon and formed into "core-type" or "shell-type" construction. Core-type construction has transformer windings on the center and the two outer legs. Shell-type construction has the transformer windings on three interior legs encircled by two outer legs. Transformer coils are usually of the "barrel" design (for small power transformers) where the low-voltage windings are placed next to the core and the higher-voltage windings are on the top of the lower-voltage winding. Cooling ducts are strategically placed within the winding. Taps are placed on the primary winding so that the voltage may be matched to the incoming utility. Three-phase core-type transformers can be connected with the primary or secondary in delta or wye.

Core-type transformers are not recommended to be connected with a wye primary with grounded neutral unless some means is provided for disconnecting all three phases in event of a fault or open primary circuit. This is due to saturation and consequential heating that can occur.

Liquid-immersed and non-ventilated transformers have their windings brought out to bushings or to junction boxes on the ends or the top of the transformers. Ventilated dry-type transformers usually have their windings terminated within the transformer enclosure to standoff insulators or bus bar terminals.

8.3 Classifications

Transformers have many classifications that are useful in the industry to distinguish or define certain characteristics of design and application. Some of these classifications are described in the following subclauses.

8.3.1 Distribution and power

These are two classifications for transformers that IEEE Std C57.12.80™-2010 defines. The power transformer transfers electric energy in any part of the circuit between the generator and the distribution primary circuits while the distribution transformer is used for transferring electrical energy from a primary distribution circuit to a secondary distribution circuit or consumer's service circuit. These definitions would appear to suit utility applications. In industrial and commercial applications, the definition of power transformer is essentially the same, while a distribution transformer could be considered one that transfers energy to a voltage which can be utilized by a load. Most transformers applied in industrial and commercial applications have primary windings rated 34.5 kV or less, and include low-voltage transformers. They may have low-voltage windings rated for either medium voltage (generally 2400 V to 4160 V) or low voltage. Power transformers may also include primary substation types that have high-voltage windings rated higher than 34.5 kV and used for utility interties where the facility is being served at transmission or sub-transmission line voltage levels.

Besides the definitions prescribed by IEEE, those who apply transformers should also be aware of relevant definitions cited in government regulations. Government mandates for minimum transformer efficiency levels were established first for low-voltage dry-type distribution transformers in 2005 and then followed by standards for medium-voltage dry-type and liquid-type distribution transformers in 2007. In these regulations, the distribution transformer was defined by the following:

a) Has an input voltage of 34.5 kV or less;

b) Has an output voltage of 600 V or less; and

c) Is rated for operation at a frequency of 60 Hz; however, the term ''distribution transformer'' does

   not include:

   1) A transformer with multiple voltage taps, the highest of which equals at least 20% more than the lowest;

   2) A transformer that is designed to be used in a special purpose application and is unlikely to be used in general purpose applications, such as a drive transformer, rectifier transformer, autotransformer, uninterruptible power system transformer, impedance transformer, regulating transformer, sealed and non-ventilating transformer, machine tool transformer, welding transformer, grounding transformer, or testing transformer. [B16]

8.3.2 Autotransformers

In this type of transformer, the primary and secondary windings are electrically connected so that part of the winding is common to both the primary and secondary. A simplified circuit of an autotransformer is shown in Figure 19.

In this figure, an input voltage V_1 is applied across XZ, which has N_1 turns. The exciting current flows in the winding through XYZ, so the secondary voltage V_2, across YZ, is

$$\frac{N_2 \times V_1}{N_1} \tag{9}$$

with N_2 being the number of turns in YZ.

In an autotransformer, part of the power is transformed by conduction and the other part is by transformer action. This is the fundamental difference between a potential divider and an autotransformer. In a potential divider, almost the entire power flows by conduction, creating more losses than in the autotransformer. The input current in a potential divider must be higher than the output current, but in an autotransformer this is not the case.
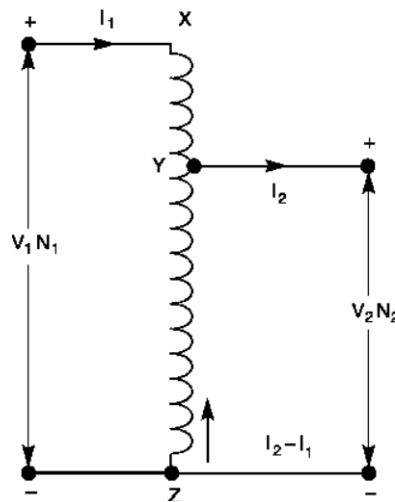

Figure 19—Typical autotransformer

In general, autotransformers are used when the transformation ratio is three or less and the electrical isolation of the two windings is not required. The application of autotransformers includes the following:

 a) Power distribution (lowering and raising voltage level)—"buck-boost" operation

 b) Induction motor starters on a selected basis

 c) Small variable-voltage power supply units

A characteristic use of autotransformers is illustrated by the following example. In the past, 600 V systems were common within certain industries. The conversion to 480 V could be accomplished by the use of a standard 480 V to 120 V transformer. The 480 V winding was connected in series with the 120 V winding, thus obtaining 600 V. The neutral was common to both systems. After the source was converted to 480 V, the same buck-boost transformer could be turned around and used to convert 480 V to 600 V for the

remaining equipment until it could be converted to the 480 V level. At the conclusion of the conversion, the standard 480 V to 120 V transformer could be used for lighting use. Thus, the same transformer served three purposes. Their application is covered in Article 450 of the NEC®.

The advantages of autotransformers are as follows:

a) For the same input and output; the weight of conductor, core material, and insulation of an autotransformer is less than that of a two-winding transformer:

$$\begin{pmatrix} \text{weight of conductor} \\ \text{in autotransformer} \end{pmatrix} = \left(1 - \frac{N_2}{N_1}\right) \times \begin{pmatrix} \text{weight of conductor in} \\ \text{two-winding transformer} \end{pmatrix} \tag{10}$$

Thus, if the transformation ratio is close to unity, the autotransformer is much less expensive than an equal-sized two-winding transformer.

b) The efficiency of an autotransformer is higher than that of a two-winding transformer for the following reasons:

1) Fewer windings result in lower losses.

2) Since part of the energy transfer takes place by conduction, the exciting current is lower, creating lower reactance and losses.

c) The reduction of ohmic resistance by reduction of conductor material, as well as the reduction of impedance by reduction of leakage flux and reactance due to presence of common winding, produce lower leakage impedance, thus creating a superior voltage regulation.

The disadvantages of autotransformers are as follows:

a) The electrical connection between primary and secondary winding can be hazardous in step-down operations when an open circuit occurs in the common winding (the low-voltage side will experience high voltage).

b) The available fault current is higher than the comparable two-winding transformer because of the inherently lower impedance.

c) The autotransformer provides less of a barrier to the transmission of electrical noise than does a comparable two-winding transformer.

8.3.3 Substation or unit substation transformer

The substation transformer for industrial plant and commercial service is an integral three-phase unit, as compared to three single-phase units. The advantages of the three-phase unit, such as lower cost, higher efficiency, less space, and elimination of exposed interconnections, have contributed to its widespread acceptance.

The term "substation transformer" usually denotes a power transformer with direct cable or overhead line termination facilities that distinguish it from a unit substation transformer designed for integral connection to primary or secondary switchgear, or both, through enclosed bus connections. The unit substation classification is further defined by the terms primary and secondary. The primary unit substation transformer has a secondary or load-side voltage rating of 1000 V or higher, whereas the secondary unit substation transformer has a load-side voltage rating of less than 1000 V.

Most transformer ratings and design features have been standardized by ANSI and NEMA. The selection of other than standard ratings will usually result in higher costs. Standard self-cooled ratings are provided in Table 14.

8.3.3.1 Substation transformers

Used with outdoor substations, they are rated 750 kVA to 5000 kVA for single-phase units and 750 kVA to 25 000 kVA for three-phase units. The primary voltage range is 2400 V and up. Taps are usually manually operated while de-energized; but automatic load tap changing may be obtained. The secondary voltage range is 480 V to 13 800 V. Primaries are usually delta connected, and secondaries are usually wye connected because of the ease of grounding the secondary neutral. The insulation and cooling medium is usually liquid. High-voltage connections are on cover-mounted bushings. Low-voltage connections may be cover-mounted bushings or an air terminal chamber.

8.3.3.2 Primary unit substation transformers

A primary unit substation consists of a close-coupled arrangement of enclosed medium-voltage equipment, a power transformer, and enclosed secondary medium-voltage equipment. Used with their secondaries connected to medium-voltage switchgear, they are rated 1000 kVA to 20 000 kVA and are three-phase units. The primary voltage range is 6900 V to 138 000 V. The secondary voltage range is 2400 V to 34 500 V. Taps are usually manually changed while de-energized; but automatic load tap changing may be obtained. Primaries are usually delta-connected. The transformer type may be oil, less-flammable liquid, air, dry, cast-coil, or gas. The high-voltage connections may be cover bushings (liquid types only), an air terminal chamber, or throat. The low-voltage connection is a throat.

8.3.3.3 Secondary unit substation transformers

A secondary unit substation consists of a close-coupled arrangement of enclosed medium-voltage equipment, a power transformer, and enclosed secondary low-voltage equipment. Used with their secondaries connected to low-voltage switchgear or switchboards, they are rated 112.5 kVA to 3750 kVA and are three-phase units. The primary voltage range is 2400 V to 34 500 V. The taps are manually changed while de-energized. The secondary voltage range is typically 120 V to 480 V. The primaries are usually delta-connected, and secondaries are usually wye-connected. The transformer type may be oil, less-flammable liquid, air, dry, cast-coil, or gas. The high-voltage connections may be an air terminal chamber or throat. The low-voltage connection is a throat.

8.3.4 Network transformers

Used with secondary-network systems, they are rated 300 kVA to 2500 kVA. The primary voltage range is 4160 V to 34 500 V. The taps are manually operated while de-energized. The secondary voltages are 208 Y/120 V and 480 Y/277 V. The type may be oil, less-flammable liquid, air, dry, cast-coil, or gas. The primary is delta-connected (wye-connected can also be used, albeit rarely), and the secondary is wye-connected. The high-voltage connection is generally a network switch (on-off-ground) or an interrupter-type switch with or without a ground position. The secondary connection is generally an appropriate network protector, or a low-voltage power circuit breaker designed to provide the functional equivalent of a network protector. IEEE Std C57.12.40™-2011 applies to liquid immersed, subway- and vault-type network units. A subway-type unit is suitable for frequent or continuous operation while submerged in water; a vault-type unit is suitable for occasional submerged operation.

8.3.5 Pad-mount transformers

Pad-mounted transformers are used where conventional unit substations might be inappropriate. Since they are of tamper-resistant construction, fencing is not required. Primary and secondary connections are made in compartments that are adjacent but separated by barriers. Access is through padlocked hinged doors designed to prevent access by unauthorized persons. Where ventilating openings are provided, tamper-

resistant louvers are used. Gauges and accessories are in the low-voltage compartment. Extended ratings using fans are considered to be inappropriate and may not be available from most manufacturers as it would compromise the tamper-proof nature of the transformer. The standards governing pad-mounted transformers (IEEE Std C57.12.21™-1992, IEEE Std C57.12.22™-1993, IEEE Std C57.12.25™-1990, and IEEE Std C57.12.26™-1992) recognize power ratings only up to 2500 kVA. Nonetheless, higher kVA ratings may be available, particularly for designs with medium-voltage secondary windings.

The high-voltage terminals may be sidewall-mounted spade terminals or high-voltage separable insulated connectors. The low-voltage spade terminals are for cable connection or for busway. Optional equipment may be installed in pad-mounted transformers including fixed-mounted secondary main breakers or distribution panelboards.

8.3.6 600 Volt class distribution transformers

Used with panelboards, motor control centers, switchboards, and separately mounted, these units have outputs of 1 kVA to 500 kVA for single-phase units and 3 kVA to 1000 kVA for three-phase units. Encapsulated designs with 115 °C temperature rise are typically furnished for single-phase transformers with ratings up to 25 kVA. Beyond this, ventilated dry-type transformers are used almost exclusively for general purpose applications. Typically the primary and secondary connections are arranged on the same side of the transformer, and all terminations made from the front. Side and rear clearances, typically six inches, are required between the transformer and adjacent equipment or other surfaces for adequate ventilation. Some designs of ventilated dry-types may include automatic forced-air ventilation systems that result in a transformer that is smaller and weighs less. These transformers are provided with thermal protection that automatically trip an integral primary disconnect should the transformer temperature rise exceed the insulation rating for any reason.

Subclasses of 600V class distribution transformers include:

 a)   K-factor transformers for nonlinear loads

 b)   Harmonic mitigating transformers

 c)   Drive isolation transformers

 d)   Shielded isolation transformers

 e)   Autotransformers

 f)   Zig-zag and wye-delta grounding transformers

 g)   Encapsulated transformer

 h)   Non-ventilated transformers

8.3.6.1 K-factor-rated transformers

The Underwriters Laboratories (UL) and transformer manufacturers have established a recognized rating method called K-factor, for dry-type power transformers, to indicate their suitability for nonsinusoidal load currents. This K-factor relates transformer capability to serve varying degrees of nonlinear load without exceeding the rated temperature rise limits. The calculation of K-factor is based upon predicted losses as specified in the simplified method of IEEE Std C57.110™-2008. The limiting factor related to the overheating is again assumed to be eddy-current losses in the windings. So that K-factor may be universally applied to all sizes of transformers, the K-factor is defined on a per-unit basis in either of the two ways that follow (see UL 1561-2011 and UL 1562-1999), although Equation (12) is more generally used than Equation (11).

$$K = \sum_{h=1}^{h_{max}} \left(I_{h(pu)}^2 \times h^2 \right) \tag{11}$$

where

$I_{h(pu)}$ is the rms current at harmonic h, in per unit of rated load current of the transformer

h is the harmonic order

The K-factor used in Equation (11) is the same as the one seen in Equation (12). For rating purposes, UL has specified that the rms current of any single harmonic greater than the 10th harmonic be considered as no greater than $1/h$ of the fundamental rms current. This limitation is an attempt to compensate, in a practical manner, for otherwise overly conservative results at higher harmonic frequencies.

$$K = \frac{\sum_{h=1}^{h_{max}} \left(f_h^2 \times h^2 \right)}{\sum_{h=1}^{h_{max}} \left(f_h^2 \right)} \tag{12}$$

where

f_h is the frequency, in hertz, of harmonic h.

The current in Equation (12) is expressed on a per-unit basis such that the sum of the individual currents times the harmonic number squared is one (this is handy for checking the results of the calculation). Thus for a linear load current, the K-factor is always one (unity).

For any given nonlinear load, if the harmonic current components are known, the K-factor can be calculated (or better yet, measured) and compared to the transformer's nameplate K-factor. As long as the load K-factor does not exceed the transformer K-factor, the transformer is being operated in accordance with this part of its NRTL listing requirements and the related NEC® requirements.

An example of a nonlinear load's K-factor is shown in Table 13. UL lists the K-factor nameplate rating for dry-type transformers under UL 1561-2011 and UL 1562-1999. Standard K-factor ratings are 4, 9, 13, and 20, with special ratings of 30, 40, and 50 that are available from some vendors. The K-9 rating is usually skipped over in favor of the K-13 rating since it is typically harder to find on the market.

Testing with a nonlinear load of appropriate K-factor is the preferred method for transformer K-factor rating testing. However, due to practical limitations, the most common method used by the NRTLs at present employs an overload of fundamental load current to simulate harmonic loading. This test method is described in UL 1561-2011 and UL 1562-1999 and requires an adjustment to compensate for harmonic losses. The test is based upon heat dissipation of the transformer without overheating any of its components or connections.

Transformers that are NRTL K-factor rated also possess certain mandated electromechanical construction characteristics not normally found in transformers without K-factor rating. These characteristics are an important part of the safety factor provided by the properly listed K-factor rated transformer. The most important of these requirements is that the neutral current path (buses, terminals, etc.) within the three-phase, wye-connected secondary transformer be designed to safely carry a continuous rms current of two times the maximum rated rms line current (e.g., this path is 200% rated for ampacity). This is done to ensure that a safe current-carrying capability exists in this path that is subject to excessively high rms currents resulting from triplen harmonics associated with line-neutral connected nonlinear loads. This

important safety feature is typically not found in standard transformers that are not K-factor rated and that may be operating with harmonic loads under a de-rating condition, as discussed previously.

Table 13 —Example calculation of a nonlinear load's K-factor

Harmonic number h	Nonlinear load current I_h (%)	I_h^2	$I_h = \sqrt{I_h^2 / \sum I_h^2}$	I_h^2	$I_h^2 h^2$
1	100	1.000	0.909	0.827	0.827
3	33	0.109	0.300	0.090	0.811
5	20	0.040	0.182	0.033	0.827
7	14	0.020	0.127	0.016	0.794
9	11	0.012	0.100	0.010	0.811
11	9	0.008	0.082	0.007	0.811
13	8	0.006	0.073	0.005	0.895
15	7	0.005	0.064	0.004	0.912
Total		1.20		0.992	6.688
				K-factor = 6.688	

8.3.6.2 Harmonic mitigating transformers

The K-factor transformer has an advantage over a conventional transformer in that it has been designed and evaluated to be used with harmonic rich loads. However, it does not improve the distorted wave shapes; it just survives them.

The harmonic canceling transformer does improve the wave shape by canceling harmonic flux in the core of the transformer, thus reducing the distortion of the voltage wave shape. It also improves the transformer's overall efficiency by reducing the heat losses due to harmonic loads.

A simple example of a "harmonic canceling" transformer is a zigzag transformer. As shown in Figure 20, a zigzag transformer has two coil windings for each phase. By reversing the direction that the second coil winds around the core, the direction of the flux created in the core by the second winding is the opposite from the first winding. For the fundamental (60 Hz) current, each phase current is shifted 120° from the other two phases, and the flux in each leg of the transformer's core is the sum of two phase currents through half of the total winding. The triplen harmonic currents, however, are all in phase with each other, and therefore cancel the triplen harmonic flux in the transformer core to the extent that they are balanced among the three phases.
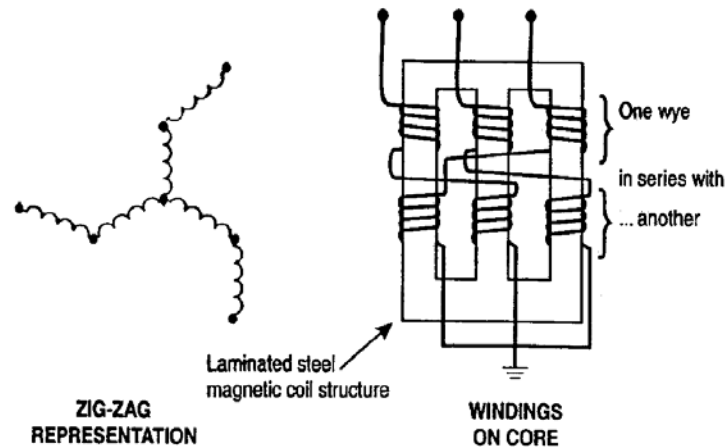
Figure 20 —Winding configuration for a zigzag transformer

NOTE 1—The above figure shows an example of a winding configuration of a zigzag transformer. In a harmonic cancellation application, the neutral of the zigzag winding would be connected to the system neutral conductor(s) on the secondary side of the transformer. The neutral would be grounded in accordance with the relevant codes or standards.

NOTE 2—The zigzag winding must be wound around a three-legged iron core similar to that shown in the figure. Zigzag windings employing separate single-phase iron cores will not perform as intended.
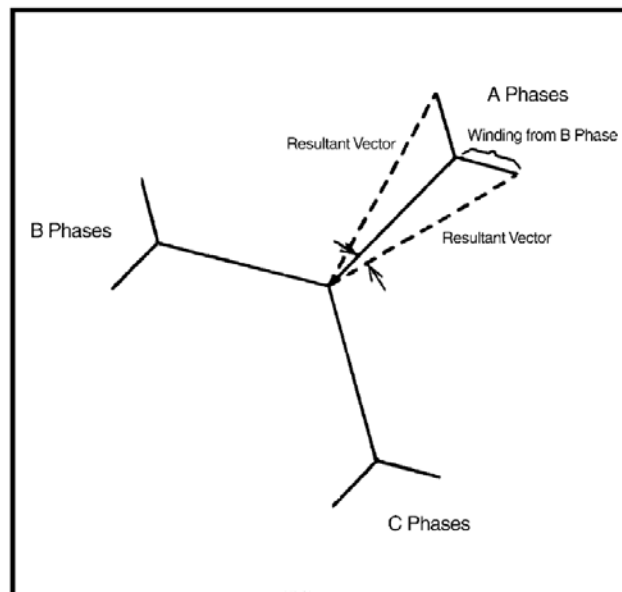

Figure 21 —Phase shift of harmonic cancelling transformer

Adjustable-speed drives (ASDs) are another common source of harmonic current distortion. In this instance, the 5th and 7th harmonics are often a larger concern than the third harmonic. Harmonic canceling transformers have also been designed for this application. As shown in Figure 21, each secondary winding has multiple sections that are wound around several different sections of the transformer's core. This creates a phase shift of 30° (each direction) from the main section of the secondary winding. The 30° phase shift in turn causes the 5th and 7th harmonics of one phase to cancel some of the harmonics from another phase.

8.3.6.3 Drive isolation transformers (DIT)

These units are designed for the special requirements of ac and dc drives, allow for the high surge, harmonic, and offset currents, reduce the transient generation into the supply power line, and buffer SCR drive current surges. The coils are rated 1.5 kVA to 25 kVA single-phase and 15 kVA to 220 kVA three-phase. Since these transformers are designed for use with motor loads, the available standard voltage ratings will correspond to that of motors (e.g., 230 Vac, 460 Vac). There are no standards specifically for DITs. Designs may be evaluated to UL 1561 for harmonic heating and designed to the typical harmonics of IEEE Std 519™-1992.

To assure that the transformer is applied properly, the designer should consult the transformer manufacturer for:

a) The minimum reactance (e.g., 3%, or 4%, or other value)

b) Withstand ratings (e.g., Withstand overcurrent of 150% of the rated load for 60 s or 200% for 30 s)

c) Duty cycle (e.g., One start every two h)

8.3.6.4 Shielded isolation transformers

These units are used to provide extraordinary isolation for sensitive electronics. One of the benefits of an isolation transformer installed at the load is reduced common-mode noise. Adding an isolation transformer at the load with a secondary neutral that can be bonded to ground will eliminate the upstream common-mode noise. An isolation transformer furnished with an electrostatic shield will also help reduce normal-mode noise. The shield is a conductive foil between the primary and secondary windings and reduces noise under 100 kHz. The shield must be grounded to function properly. In addition to the grounded electrostatic shield between windings, these types of transformers can be supplied with noise suppressors and voltage surge suppressors to further condition the voltage to the load.

8.3.6.5 Low-voltage autotransformers

Low-voltage autotransformers can be used effectively to compensate for mismatches between the supplied voltage and the voltage tolerance of the load when the voltage difference is not too great and when load isolation is not required. In these situations, the autotransformer is a very economical solution because the kVA rating of the autotransformer winding is determined from the voltage adjustment that is required, rather than the entire line-to-line or line-to-neutral voltage. For example, a single-phase autotransformer stepping up from 208 Vac to 240 Vac and carrying a load of 100 A must be rated a minimum of 3.2 kVA (100 A × [240 V – 208 V]), whereas an isolation transformer designed for the same thing must be rated 24 kVA (100 A × 240 V).

Low-voltage auto transformers are rated 0.05 kVA to 3 kVA single-phase and may be configurable for loads as high as 300 kVA three-phase.

8.3.6.6 Zigzag grounding transformers

These are special three-phase autotransformers. The applications for these units include:

a) Establishing a neutral for a four-wire secondary distribution system from a three-wire delta secondary, such as changing a 480 V three-wire system to a 480 Y/277 V system;

b) Reducing zero sequence harmonics, but without changing the system type between delta and wye;

c) Reducing high neutral currents.

Refer to NEC® Section 450.6, Grounding Autotransformers, for application rules.

When applied to a derive a 480 Y/277 V system, the zigzag grounding transformer is rated to carry the third harmonic currents flowing in the neutral plus the unbalanced current flowing in the neutral. The short-time kVA rating of a grounding transformer then is the rated line-to-neutral voltage times the rated neutral current. In addition, the transformer is rated to carry ground-fault current for a definite time, depending upon specification, of 10 s or 1 min.

8.3.6.7 Encapsulated transformers

These 600 V class totally-enclosed non-ventilated transformers are generally available for use in harsh environments. Single-phase units are available through 100 kVA, and three-phase units are available through 300 kVA.

8.3.6.8 Non-ventilated transformers

These 600 V class totally enclosed non-ventilated transformers are generally available for use in hazardous environments, NEC® Class I Division II, Groups C and D, and harsh environments. Single-phase units are available from 10 kVA through 100 kVA, and three-phase units are available from 15 kVA through 300 kVA.

8.4 Specifications

In specifying a transformer for a particular application, the following should be included:

a) Items comprising the rating structure

   1) Rating in kilovoltamperes or megavoltamperes

   2) Single-phase or three-phase

   3) Frequency

   4) Voltage ratings

   5) Voltage taps

   6) Winding connections, delta or wye

   7) Impedance (base rating)

   8) Basic impulse insulation level (BIL)

   9) Temperature rise

b) Desired construction details

   1) Insulation medium, dry or liquid-type (see 8.9)

   2) Indoor or outdoor service

   3) Accessories

   4) Type and location of termination facilities

   5) Sound level limitations if the installation site requires this consideration

   6) Manual or automatic load tap changing

   7) Grounding requirements

8) Provisions for future cooling of the specified type

9) Radiator type and thickness (liquid-type units)

10) Special painting requirements

11) Category of enclosure (A, B, or C) for personnel protection per Table 1 in IEEE Std C57.12.55™-1987.

    Category "A" indoor or outdoor enclosures: Category "A" indoor or outdoor enclosures are intended (1) for ground level use in installations subject to deliberate, unauthorized acts by members of the unsupervised general public and (2) primarily to provide a degree of protection against contact with the enclosed equipment.
    Category "B" indoor or outdoor enclosures: Category "B" indoor or outdoor enclosures are intended (1) for use in installations not subject to deliberate, unauthorized acts by members of the unsupervised general public and (2) primarily to provide a degree of protection to unauthorized and untrained personnel against incidental contact with the enclosed equipment.
    Category "C" indoor or outdoor enclosures: Category "C" indoor or outdoor enclosures are intended (1) for use in installations in secured areas generally inaccessible to unauthorized and untrained persons and (2) to provide a degree of protection against contact with the enclosed equipment.

12) Designation of enclosure type (103, 103R, 103S, or 104) for outdoor non-hazardous locations per Table 7 in IEEE Std C57.12.55™-1987.

    Type 103 enclosures are intended for outdoor use primarily to provide a degree of protection against windblown dust, rain, sleet, and external ice formation. They shall meet rain, external-icing, dust, and corrosion-resistance design tests. They are not intended to provide protection against conditions such as internal condensation or internal icing.
    Type 103R enclosures are intended for outdoor use primarily to provide a degree of protection against falling rain, sleet, and external ice formation. They shall meet rod-entry, rain, external-icing, and corrosion-resistance design tests. They are not intended to provide protection against conditions such as dust, internal condensation, or internal icing.
    Type 103S enclosures are intended for outdoor use primarily to provide a degree of protection against windblown dust, rain, and sleet and to provide for operation of external mechanisms when ice laden. They shall meet rain, external icing, dust, and corrosion-resistance design tests. They are not intended to provide protection against conditions such as internal condensation or internal icing.
    Type 104 enclosures are intended for indoor or outdoor use primarily to provide a degree of protection against windblown dust, rain, sleet, splashing water, and hose-directed water. They shall meet hosedown, dust, external-icing, and corrosion-resistance design tests. They are not intended to provide protection against conditions such as internal condensation or internal icing.

Consideration should be given to energy conservation features in the transformer specification that may, in some instances, be mandated by law or by individual company policy. Most dry-type low-voltage transformers and medium-voltage transformers applied in the United States are required by law to have a minimum efficiency.

The minimum efficiencies of low-voltage dry-type transformers are defined in NEMA TP-1 while the minimum efficiencies of medium-voltage liquid-type and dry-type transformers are defined in a final rule issued by the U.S. Department of Energy (DOE) [B16] [B18] [B19]. Standard designs that exceed these minimum levels have begun to be furnished by suppliers. One such design of low-voltage dry-type transformers is referred to by the DOE designation Candidate Service Level 3 (CSL-3). This level of efficiency is characterized by having an efficiency that exceeds NEMA TP 1 levels by 0.8 percent. In practical terms, these designs usually have very low no-load losses, typically about one-half that of a standard NEMA TP 1-compliant transformer. This being the case, they are most effective in applications where the transformer has little or no load for long periods of time, such as in school facilities.

Where efficiency is of concern, several cost-analysis techniques are used to formalize procurement decisions with the goal of maximizing efficiency or minimizing overall life-cycle cost. In either case, the following information about the transformer should be supplied to the prospective vendors based on annualized operating projections:

— The cost in dollars/kW at which no-load losses are valued;

— The cost in dollars/kW at which load losses are valued; and

— The percentage of the transformer rating at which load losses will be evaluated during the bid-comparison process.

Given this information, a prospective vendor can then establish the optimum proportion of conductor and core material to be used in the construction of the transformer. In this manner, the cost of inefficiency can be factored into the initial capital expenditure. This process is detailed in IEEE Std 739™-1995.

8.5 Transformer power ratings

Ratings in kilovoltamperes or megavoltamperes will include the self-cooled rating at a specified temperature rise, as well as the forced-cooled rating if the transformer is to be so equipped.

Capability beyond the base self-cooled rating may be provided though one of two methods. One is the use of forced cooling equipment to increase the flow of a cooling medium either internally or externally and increase heat dissipation over that of convective fluid flow. The second is the use of lower temperature rise designs that create additional thermal margin between the temperature rise at the base self-cooled rating and the insulation temperature rating to allow additional capacity. Any distribution system plan that anticipates using transformer capacity above the self-cooled base rating of the transformer requires that the system designer evaluate:

a) Fluid expansion and pressure in sealed units

b) Thermal limitations of connected equipment

c) Wiring voltage drops and voltage drops due to transformer regulation

d) Load cycle and duration

e) Ambient conditions over the period

f) Associated ventilation or cooling equipment in the space for units installed indoors

All the preferred kVA ratings in Table 14 are available as standard at all voltage ratings and ratios. The smaller sizes apply to lower voltages, and the larger sizes to higher voltages. Voltage ratings and ratios should be selected in accordance with available standard equipment. This is recommended from the viewpoint of cost and time for initial procurement and for ready replacement.

In most small size commercial projects, the 208 Y/120 V secondary voltage is used because the majority of load is lighting and small appliances. A secondary voltage of 480 Y/277 V, in addition to the 208 Y/120 V circuits, may be required when loads are electric motors or have large lighting requirements. A three-phase transformer secondary voltage should be selected at 480 Y/277 V. Phase-to-neutral 277 V circuits can serve lighting and small motors used in HVAC systems.

8.5.1 Standard ratings

The standard self-cooled ratings are listed in Table 14. Table 15 contains the transformer cooling codes, which have been harmonized between the IEEE and the IEC, and the previous IEEE standard codes as there are many units in service that carry these codes. The harmonized codes are designed as follows:

a) First letter: Internal cooling medium in contact with the windings

   O Mineral oil or synthetic insulating liquid with fire point less than 300C

   K Insulating liquid with fire point greater than 300C

   L Insulating liquid with no measurable fire point

b) Second letter: Circulation mechanism for internal cooling medium

   N Natural convection flow through cooling equipment and windings

   F Forced circulation through cooling equipment (cooling pumps), natural convection flow in windings (non-directed flow)

   D Forced circulation through cooling equipment, directed from the cooling equipment into at least the main windings

c) Third letter: External cooling medium

   A Air

   W Water

d) Fourth letter: Circulation mechanism for external cooling medium

   N Natural convection

   F Forced circulation (fans, pumps)

Table 14 —Liquid-immersed and dry-type transformer standard base kVA ratings

Single-phase				Three-phase			
1 (1)	50	833	8333	15	300	3750	25 000
3 (1)	75	1250	10 000	30	500	5000	30 000
5	100	1667	12 500 (2)	45	750	7500	37 500 (2)
10	167	2500	16 667 (2)	75	1000	10 000	50 000 (2)
15	250	3333	20 000 (2)	112.5	1500	12 000	60 000 (2)
25	333	5000	25 000 (2)	150	2000	15 000	75 000 (2)
37.5	500	6667	33 000 (2)	225	2500	20 000	100 000(2)
NOTE 1—Dry-type transformer only NOTE 2—Liquid-immersed transformer only							

Source: Based on IEEE Std C57.12.00™-2010 and IEEE Std C57.12.01™-2005.

The preferred ratings for forced-air-cooled operation to be provided for each self-cooled rating are listed in IEEE Std C57.12.10™-1997 for liquid-type power transformers and IEEE Std C57.12.51™-2008 for ventilated dry-type power transformers. A comparison of the ratings shows that a fixed percentage increase must be provided which depends on the number of phases, the self-cooled rating, and the transformer type (liquid or dry):

— Forced-air-cooled ratings (AF) of ventilated dry-type transformers will provide approximately 33% higher capacity over that of the self-cooled rating (AN).

— Liquid-type power transformers with single-phase self-cooled ratings (ONAN) up to 1667 kVA and three-phase self-cooled ratings (ONAN) up to 2000 kVA will have a forced-air-cooled rating (ONAF) that provides approximately 15% additional capacity to that of the self-cooled rating.

— Liquid-type power transformers with single-phase self-cooled ratings (ONAN) of 2500 kVA to 8333 kVA and three-phase self-cooled ratings (ONAN) of 2500 kVA to 10 000 kVA will have a forced-air-cooled rating (ONAF) that provides approximately 25% additional capacity.

— Three-phase liquid-type transformers with self-cooled ratings (ONAN) 12 000 kVA and larger may have one or two stages of forced cooling. The first stage will provide a 33% increase in rating over the self-cooled rating and a second stage, if provided, will provide a 66.7% increase over that of the self-cooled rating.

As a minimum, the self-cooled rating should be at least equal to the expected peak demand with an allowance for projected load growth. In double-ended substations where one transformer may be required to feed both its normal load as well as the load on the other side of the tie breaker, the extended rating of the transformers should be equal to the expected peak demand of the combined loads on both sides of the tie breaker, along with an allowance for projected load growth.

Table 15 —Classes of transformer cooling systems

Class from harmonized standard	Class from previous IEEE standard	Method of cooling
ONAN	OA	Liquid-immersed, self-cooled
ONAN/ONAF	OA/FA	Liquid-immersed, self-cooled/forced-air-cooled
ONAN/ONAF/ONAF	OA/FA/FA	Liquid-immersed, self-cooled/forced-air-cooled/forced-air-cooled
ONAN/ONAF/OFAF	OA/FA/FOA	Liquid-immersed, self-cooled/forced-air-cooled/forced-liquid-cooled
ONAN/ OFAF /OFAF	OA/FOA/FOA	Liquid-immersed, self-cooled/forced-air, forced-liquid-cooled/forced-air, forced-liquid-cooled
OFAF	FOA	Liquid-immersed, forced-liquid-cooled with forced-air-cooled
OFWF	FOW	Liquid-immersed, forced-liquid-cooled with forced-water-cooled
ONWN	OW	Liquid-immersed, water-cooled
ONWN	OW/A	Liquid-immersed, water-cooled/self-cooled
AN	AA	Dry-type,[a] ventilated self-cooled
AF	AFA	Dry-type,[a] ventilated forced-air-cooled
AN/AF	AA/FA	Dry-type,[a] ventilated self-cooled/forced-air-cooled
—	ANV	Dry-type,[a] non-ventilated, self-cooled
—	GA	Dry-type,[a] sealed self-cooled

Source: IEEE Std C57.12.00™-2010 and IEEE Std C57.12.01™-2005

[a]Dry-type: Including those with solid cast and/or resin-encapsulated winding.

8.5.2 Temperature rise

The transformer power ratings (kVA) are limited by the maximum temperature rise that the transformer insulation system can tolerate. The standard average winding temperature rise (by resistance test) for the modern liquid-immersed transformer is 65 °C, based on an average ambient of 30 °C (40 °C maximum) for any 24-hour period. Liquid-immersed transformers may be specified with a 55 °C/65 °C rise to permit 100% loading with a 55 °C rise, and 112% loading at the 65 °C rise. Older, oil-filled transformers were rated based on 55 °C rise. Many of these are still in service. The transformer nameplate will indicate the temperature rise upon which its capacity is based.

Dry-type transformers have five insulation system temperature classes as mentioned in IEEE Std C57.12.01™-2005. These insulation classes are 130 °C, 150 °C, 180 °C, 200 °C, and 220 °C. The modern 220 °C insulation class ventilated dry-type transformer has an average winding temperature rise (by resistance) of 150 °C, based on an average ambient temperature of 30 °C, and a 24-hour period maximum ambient temperature of 40 °C. The allowable hot-spot winding temperature rise is 30 °C, resulting in a maximum hot-spot temperature of 220 °C.

Vacuum cast coil transformers are constructed with a 185 ºC insulation system. They have an average winding temperature rise (by resistance) of 115 °C, based on an average ambient temperature of 30 °C, and a 24-hour period maximum ambient temperature of 40 °C.

Low-loss, high-efficiency, ventilated dry-type transformers can be specified with 115 °C or 80 °C rise. These lower temperature rise units have longer life expectancies. For instance, a 115 °C transformer has a life expectancy about ten times greater than that of a 150 °C rise transformer. Dry-type transformers of 115 °C and 80 °C rise also have, respectively, an approximate emergency overload capability of 15% and 35% when supplied with 220 °C insulation systems. These extended ratings from low temperature rise design are not necessarily included on the transformer nameplate, but they can be if the purchaser specifies that the transformer be designed for this purpose.

In the case of both dry-type and liquid-filled transformers, extended ratings from low temperature rise can be combined with that of forced-air equipment. The total additional capacity will be the product of the combined percentages. For example, a 2000 kVA liquid-filled transformer can be loaded to nearly 129% base capacity when supplied with the combination of a 55 °C/65 °C rating and forced-air equipment. Loading of 112% is allowed from the 55 °C/65 °C rating and another 115% loading results from the forced-air equipment ($1.12 \times 1.15 = 1.288$).

Transformers have certain overload capabilities, varying with ambient temperature, preloading, and overload duration. These capabilities are defined in IEEE Std C57.91™-2011 and IEEE Std C57.96™-1999 for both the liquid-insulated and dry types.

Both liquid-immersed and dry-type transformers are available with lower core and coil watt loss designs at higher initial prices but with significantly lower overall operating costs due to the higher energy efficiency.
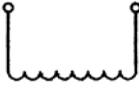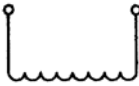
8.6 Transformer voltage ratings

The transformer voltage ratings will include the primary and secondary continuous-duty levels at the specified frequency, as well as the BIL for each winding. The continuous rating specified for the primary winding will be the nominal line voltage of the system to which the transformer is to be applied, and preferably within ±5% of the normally sustained voltage. The secondary or transformed voltage rating will be the value under no-load conditions. The change in secondary voltage experienced under load conditions is termed regulation and is a function of the impedance of the system and the transformer and the power factor of the load. Table 16 and Table 17 illustrate the proper designation of voltage ratings.

The BIL for a transformer winding signifies the design and tested capability of its insulation to withstand transient overvoltages from lightning and other surges. Standard values of BIL established for each nominal voltage class are listed in Table 18 and Table 19. A description of test requirements for these values is given in IEEE Std C57.12.00™-2010. Transformer bushings may be specified with extra creepage distance and higher than standard BIL ratings if required by local conditions or users' practices.

Protecting the transformer windings from high-voltage surges with surge arresters will allow the use of a transformer with a lower BIL and still provide for better performance. For high-voltage and high kVA-rated performance transformers, this will also result in lower transformer cost. Refer to Chapter 6 of IEEE 141™-1993 (*IEEE Red Book*™) for a discussion on arrester application for the overvoltage protection of transformers. Since the BILs listed as "standard values" for the ventilated dry-type and gas-filled transformer windings are usually less than that of the liquid-immersed transformers, surge arresters should be included for the primary winding in order to obtain additional protection, or the optional higher BILs listed in IEEE Std C57.12.01™-2005 should be specified.

Table 16 —Designation of voltage ratings of single-phase windings (schematic representation)

Identifi-cation	Nomen-clature	Nameplate marking	Typical winding diagram	Condensed usage guide
(1)(a)	E	2400		E shall indicate a winding of E volts which is suitable for connection on an E volt system.
(1)(b)	E/E_1Y	2400/4160Y		E/E_1Y shall indicate a winding of E volts which is suitable for Δ connection on an E volt system or for Y connection on an E_1 volt system.
(1)(c)	E/E_1GrdY	2400/4160GrdY		E/E_1GrdY shall indicate a winding of E volts having reduced insulation which is suitable for Δ connection on an E volt system or Y connection on an E_1 volt system, transformer neutral effectively grounded.
(1)(d)	E_1 GrdY/E	12 470GrdY/7200		E_1 GrdY/E shall indicate a winding of E volts with reduced insulation at the neutral end. The neutral end may be connected directly to the tank for Y or for single-phase operation on an E_1 volt system, provided the neutral end of the winding is effectively grounded.
(1)(e)	$E/2E$	120/240		$E/2E$ shall indicate a winding, the sections of which can be connected in parallel for operation at E volts, or which can be connected in series for operation at $2E$ volts, or connected in series with a center terminal for three wire operation at $2E$ volts between the extreme terminals and E volts between the center terminal and each of the extreme terminals.
(1)(f)	$2E/E$	240/120		$2E/E$ shall indicate a winding for $2E$ volts, two-wire full kVA between extreme terminals, or $2E/E$ volts three-wire service with 1/2 kVA available only, from midpoint to each extreme terminal.
(1)(g)	$V × V_1$	240 × 480 2400/4160Y × 4800/8320Y		$V × V_1$ shall indicate a winding for parallel or series operation only but not suitable for three-wire service.

NOTE 1—E is line-to-neutral voltage of a Y winding, or line-to-line voltage of a Δ winding.
NOTE 2—E₁ is √3 E.
NOTE 3—Additional subscripts, H, X, and Y (when used) identify high-voltage, low-voltage, and tertiary-voltage windings.

Source: Reprinted from IEEE Std C57.12.00™-2010.

**Table 17 —Designation of voltage ratings of three-phase windings
(schematic representation)**

Identifi-cation	Nomen-clature	Nameplate marking	Typical winding diagram	Condensed usage guide
(2)(a)	E	2400		E shall indicate a winding that is permanently Δ connected for operation on an E volt system.
(2)(b)	E_1Y	4160Y		E_1Y shall indicate a winding that is permanently Y connected without a neutral brought out (isolated) for operation on an E_1 volt system.
(2)(c)	E_1Y/E	4160Y/2400		E_1Y/E shall indicate a winding which is permanently Y connected with a fully insulated neutral brought out for operation on an E_1 volt system, with E volts available from line to neutral.
(2)(d)	E/E_1Y	2400/4160Y		E/E_1Y shall indicate a winding that may be Δ connected for operation on an E volt system, or may be Y connected without a neutral brought out (isolated) for operation on an E_1 volt system.
(2)(e)	E/E_1Y/E	2400/4160Y/2400		E/E_1Y/E shall indicate a winding that may be Δ connected for operation on an E volt system, or may be Y connected with a fully insulated neutral brought out for operation on an E_1 volt system with E volts available from line to neutral.
(2)(f)	E_1GrdY/E	34 500GrdY/ 19 920		E_1GrdY/E shall indicate a winding with reduced insulation and permanently Y connected, with a neutral brought out and effectively grounded for operation on an E_1 volt system with E volts available from line to neutral.
(2)(g)	E/E_1GrdY/E	7200/ 12 470GrdY/ 7200		E/E_1GrdY/E shall indicate a winding having reduced insulation, which may be Δ connected for operation on an E volt system; or may be connected Y with a neutral brought out and effectively grounded for operation on an E_1 volt system with E volts available from line to neutral.
(2)(h)	$V \times V_1$	240 x 480 2400/4160Y × 4800/8320Y		operation on $V \times V_1$ shall indicate a winding, the sections of which may be connected in parallel to obtain one of the voltage ratings (as defined in a-g) of V, or may be connected in a series to obtain one of the voltage ratings (as defined in a-g) of V_1. Windings are permanently Δ or Y connected.

Source: Reprinted from IEEE Std C57.12.00™-2010.

**Table 18 —Relationships of nominal system voltage to maximum system voltage
and basic lightning impulse insulation levels (BIL) for systems 34.5 kV and below
for liquid-immersed transformers[a,b,c,d]**

Application	Nominal system voltage(kV rms)	Basic lightning impulse insulation levels (BIL) in common use (kV crest)		
Distribution	1.2	**30**		
	2.5	**45**		
	5.0	**60**		
	8.7	**75**		
	15.0	**95**	110	
	25.0	**125**	150	
	34.5	125	**150**	200
Power	1.2	**30**	**45**	
	2.5	**45**	**60**	
	5.0	**60**	**75**	
	8.7	**75**	**95**	
	15.0	**95**	**110**	
	25.0	**150**		
	34.5	**200**		

Source: Based on Table 4 of IEEE Std C57.12.00™-2010.

[a] BIL values in **bold typeface** are the most commonly used standard values.

[b] Single-phase distribution and power transformers and regulating transformers for voltage ratings between terminals of 8.7 kV and below are designed for both wye and delta connection and are insulated for the test voltages corresponding to the wye connection, so that a single line of transformers serves for the wye and delta applications. The test voltages for such transformers when operated delta connected are, therefore, higher than needed for their voltage rating.

[c] For series windings in transformers, such as regulating transformers, the test values to ground shall be determined by the BIL of the series windings rather than by the rated voltage between terminals.

[d] Values listed as nominal system voltage in some cases (particularly voltages 34.5 kV and below) are applicable to other lesser voltages of approximately the same value. For example, 15 kV encompasses nominal system voltages of 14 440 V, 13 800 V, 13 200 V, 13 090 V, 12 600 V, 12 470 V, 12 000 V, 11 950 V, etc.

Table 19 —Relationships of nominal system voltage and basic lightning impulse insulation levels (BILs) for systems 34.5 kV and below for dry-type transformers

Nominal system voltage (kV)	Basic lightning impulse insulation levels (BILs) in common use (kV crest)									
	10	20	30	45	60	95	110	125	150	200
1.2	S	1	1							
2.5		S	1	1						
5.0			S	1	1					
8.7				S	1	1				
15.0					S	1	1			
25.0						2	S	1	1	
34.5								2	S	1
S = Standard values. 1 = Optional higher levels where exposure to overvoltage occurs and higher protective margins are required. 2 = Lower levels where surge arrester protective devices can be applied with lower spark-over levels.										

Source: Reprinted from IEEE Std C57.12.01™-2005.

8.6.1 Voltage taps

Voltage taps are usually necessary to compensate for small changes in the primary supply to the transformer, or to vary the secondary voltage level with changes in load requirements.

The most commonly selected tap arrangement is the manually adjustable no-load type, consisting of four ± 2.5% steps or variations from the nominal primary voltage rating. These tap positions are usually numbered one through five, with the number one position providing the greatest number of effective turns. Based on a specific incoming voltage, selection of a higher voltage tap (lower tap number) will result in a lowering of the output voltage. The changing of tap positions is performed manually only with the transformer de-energized. On liquid-immersed and sealed transformers, the tap leads are brought to an externally operated tap changer with a handle capable of being locked in any tap position. On very small liquid-immersed transformers and most ventilated dry-type transformers, the taps are changed by moving internal links that are made accessible by a removable panel on the enclosure.

The tap selected in the transformer should be based upon maximum no-load voltage conditions. For example, a standard transformer rated 13.2 kV to 480 V may have four 2.5% taps in the 13.2 kV winding (two above and two below 13.2 kV). If this transformer is connected to a system whose maximum voltage is 13.53 kV, then the 13.53 kV to 480 V tap could be used to provide a maximum of 480 V at no-load.

In addition to the no-load taps, automatic tap-changing under load is available. There are three common applications for automatic tap-changing under load. The first of these is on substations transformers connected to either transmission line or sub-transmission line utility sources. These sources are generally not regulated, and the voltage on these lines can vary over a wider percent difference range than the load equipment can tolerate. A load tap changer on the secondary winding can be used to compensate for this.

The second application involves a special case of the above where the facility has significant on-site generation capability which is operated while connected to the utility. The interconnection agreements for

these facilities may include a requirement that the owner maintain unity power factor across the intertie. Reactive power flow is generally controlled through the voltage regulator on the generator, but a wide variance in the voltage on the intertie may be beyond the capability of the voltage regulator to control adequately. A load tap changer and automatic VAR controller can be used to resolve this issue.

The third situation where a load tap changing feature is considered desirable is when load swings are larger and more frequent or voltage levels more critical. Automatic tap changing under load can provide an additional automatic voltage adjustment, typically ±10%, in incremental steps, with continuous monitoring of the secondary terminal voltage or of a voltage level remote from the transformer. There are also low voltage regulating transformers available that are continuously adjustable, and provide adjustability to the incoming voltage on a range of –25% to +25%.

8.7 Connections

Connections for the standard two-winding power transformers are preferably delta-primary and wye-secondary. The wye-secondary, specified with external neutral bushing, provides a convenient neutral point for establishing a system ground, or can be run as a neutral conductor for phase-to-neutral load. The delta-connected primary isolates the two systems with respect to the flow of zero-sequence currents resulting from third-harmonic exciting current, secondary generated triplens due to non-linear loads, or a secondary ground fault, and may be used without regard to whether the system to which the primary is connected is three-wire or four-wire.

There can be an angular displacement of the secondary phase voltages with respect to the primary voltages on three-phase transformers. Per IEEE Std C57.12.00™-2010 and IEEE Std C57.12.01™-2005, transformers connected either wye-wye or delta-delta shall have a an angular displacement of 0° while transformers connected either delta-wye or wye-delta shall have an angular displacement of 30° with the low voltage lagging the high voltage.

In some installations, a grounded primary wye-wye transformer connection is used to minimize the problem of ferroresonance. However, this connection introduces the problem of having to cope with zero-sequence quantities during conditions of circuit unbalance. There are two methods for balancing zero-sequence ampere turns:

a) Shell-form construction can be used to provide a low-reluctance return path for the single-phase zero-sequence flux. This construction would include the five- or four-legged core. The five-legged core is a three-phase core with five legs. Coils are mounted on three of the legs with the remaining two serving as a return path for magnetic flux. Thus, the five-legged core has a path for undesirable zero-sequence flux during unbalanced conditions.

b) A delta-connected tertiary winding could circulate the required balancing ampere turns. A primary grounded transformer with a delta tertiary or equivalent delta tertiary winding will provide a source of ground fault current to system ground faults. However, a careful study must be made to determine the impact of such a ground source on the system ground fault protection and coordination. The maximum ground fault current provided by this transformer for external faults must not result in operation of primary fuses or overcurrent devices. Additionally, the transformer components must be designed to be thermally adequate to carry the maximum unbalanced currents expected during both unbalanced steady state and ground fault conditions. It should also be noted that if one primary conductor opens upstream, the tertiary winding may attempt to feed power to other loads downstream of the failure and cause an overload and eventual failure of the tertiary winding.

8.8 Impedance

The impedance voltage of a transformer is the voltage required to circulate rated current through one of two specified windings of a transformer when the other winding is short-circuited, and with the windings connected as they would be for rated-voltage operation.

An important factor in a transformer's impedance is the turns ratio between the primary and secondary windings, represented as "α." Figure 22 shows an "ideal transformer" in a dashed box and the primary and secondary resistances and reactances of a practical transformer. The secondary winding has N_2 turns of wire wound around an iron core, and the primary winding has N_1 wound over it. The turns ratio α, equals N_1 divided by N_2, and the ratio of E_1 to E_2 is also equal to α. For an "ideal transformer," there are no losses, and the primary voltage multiplied by the primary current is equal to secondary voltage multiplied by the secondary current ($E_1 I_1 = E_2 I_2$ and $I_2 = \alpha\, I_1$).

Figure 23 is the equivalent circuit of a practical transformer as seen from the primary. R_1 and X_{L1} are the resistance and reactance of the primary winding. R_m and X_{Lm} are the effect of "magnetizing current," the energy required to magnetize the iron core and create open-circuit voltage at the secondary terminals. R_2 and X_{L2} are the resistance and reactance of the secondary winding, and Z_L is the impedance of the load. Notice that R_2, X_{L2}, and Z_L are each multiplied by the turns ratio squared (α^2).
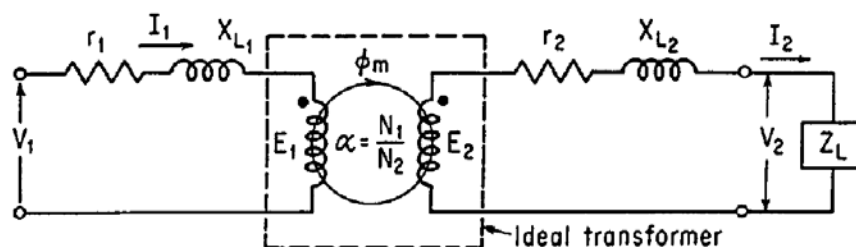

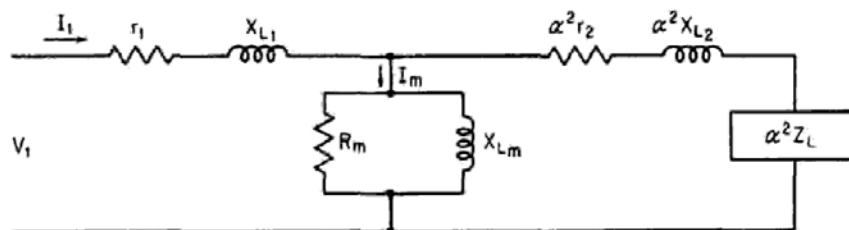**Figure 22—Transformer impedances and turns ratio *α***

Figure 23—Transformer equivalent circuit

As an example, "α" for a single-phase 480 V to 120 V transformer is 4. If Z_L is a 10 Ω resistor, 12 amps will flow through the resistor and the secondary winding of the transformer. To "push" a current of 12 amps through the secondary, the primary current would have to be $12/\alpha$, which in this case is 3 A, plus the magnetizing current (through R_m and X_{Lm}). Looking at just the load component of current, the 3 A, and dividing it into the primary voltage of 480, shows what the 10 Ω resistor is equivalent to, at the primary side, $480/3 = 160$, which is $10 \times \alpha^2$. Impedance voltage is normally expressed as a percent value of the rated voltage of the winding in which the voltage is measured on the transformer self-cooled rating in kilovolt-amperes. This eliminates the need to factor in the turns ratio, which would be required if the impedance was expressed in ohms. For example, the determination of a transformer internal impedance (*%Z*) is typically done at field level per Equation (13).

$$\%Z = 100\left(\frac{I_{\text{full load}}}{I_{\text{short-circuit maximum}}}\right) \tag{13}$$

Due to the method of testing in a transformer factory or test-stand setting, the calculation of %Z requires knowledge of the following:

a)   The input voltage necessary to make the current in a short-circuited secondary equal to the rated current

b)   The rated input voltage

Then, the transformer internal impedance, again expressed as a percent (%Z), is the ratio of item a) to item b), multiplied by 100.

Two examples of *%Z* and its use follow:

1)   A transformer with a 5% internal impedance allows 20 times its rated current to flow during short-circuit conditions [(100/5) = 20], assuming sufficient fault current is available on its primary. This is more than sufficient to ensure swift operating times for overcurrent protective devices clearing faults. Conversely, a 20% *Z* would limit available fault current to no more than 5 times full-load current, and this would not be sufficient to ensure a prompt operation of a main overcurrent protective device (at least 10 times current is often recommended).

2)   Although not to be confused with the subject of voltage regulation, the *%Z* of a transformer does have a relationship to load changes and output voltage stability as follows: At a given power factor, a transformer with a 5% internal impedance also allows a 5% voltage variation to occur on its output from no-load (where the voltage is equal to the primary voltage times the turns ratio) to full-load (where the voltage is 5% lower than at no-load). With a transformer of 2.5% Z, this would be reduced to a 2.5% variation. Conversely, a 20% Z rating would allow a 20% voltage variation, which is too great for most electronic loads to tolerate without malfunction (see FIPS Pub 94 [B20]).

It is desirable to have low internal impedance, such that supply voltage variances are small for normal swings in load currents. However, if the source impedance is too low, possible short-circuit current can be excessive to the point that special circuit breakers or supplementary current-limiting fuses are required to interrupt fault current.

Note that to determine the full range of voltage variation from a transformer's output under varying load conditions, the impedance characteristics of the primary circuit supplying it must also be considered. Such series impedance will act in concert with the transformer's *%Z* and will in almost all cases produce larger voltage variations than indicated above for *%Z* alone.

The percent impedance voltage levels considered as standard for two-winding transformers are listed in Table 20 and Table 21. A value specified above or below those listed may result in higher costs. The percent impedance voltage of a two-winding transformer shall have a tolerance of 7.5% of the specified value. For three-winding or auto-transformers, the manufacturing tolerance is ±10%. The manufacturing tolerance is ±10% from the specified impedance if the specified impedance is less than or equal to 2.5%, and ±7.5% if it is over 2.5%. When considering a low-impedance voltage level, as compared to figures shown in Table 20 and Table 21, it should be remembered that the standard transformer is designed with a limited ability to withstand the stresses imposed by external faults. Refer to IEEE Std C57.12.00™-2010 for short-circuit requirements and IEEE Std C57.12.90™-2010 for short-circuit test levels. A combined primary system and transformer impedance voltage permitting rms symmetrical fault magnitudes in excess of these standards should be avoided.

With respect to impedance, transformers are generally considered suitable for parallel operation if their impedances match within 5%. The importance of minimizing the mismatch becomes greater as the total

load approaches the combined capacity of the paralleled transformers since load division is inversely proportional to the internal impedance. The impedance mismatch should be checked throughout the entire range of taps (both load and no-load).

Impedances of 600 V general-purpose distribution transformers are not standardized. For distribution system planning, including voltage drop, load flow, and short-circuit calculations, it is recommended that the impedances be obtained from the manufacturers. The impedances vary among manufacturers and vary by design and rating of the transformer.

Table 20 —BIL and percent impedance voltages at self-cooled
(OA) rating for liquid-immersed transformers
(833/958 kVA and above—single-phase
750/860 kVA and above—three-phase)

High-voltage BIL (kV)	Without load tap changing		With load tap changing
	Low-voltage 480 V	Low-voltage 2400 V and above	Low-voltage 2400 V and above
≤110	5.75[a]	5.5*	—
150	6.75	6.5	7.0
200	7.25	7.0	7.5
NOTE—This table covers general percentage impedances values accepted industry-wide. Above-referenced values should be utilized, and manufacturers should be consulted for the transformers not included in the tables.			

Source: Based on Table 3 of IEEE Std C57.12.10™-2010 and Table 5 of IEEE Std C57.12.36™-2007.

[a]For transformers greater than 5000 kVA self-cooled, these values shall be the same as those shown for 150 kV high-voltage BIL.

Table 21 —BIL and percent impedance voltage for dry-type transformers
(501 kVA and above)[a]

High-voltage BIL (kV)	Percent impedance
95 and below	5.75
Above 95	7.0

Source: Based on Table 4 of IEEE Std C57.12.51™-2008.

[a]Ventilated dry-type network transformers rated up to 1000 kVA are required to have a 5% impedance, and ratings greater than 1000 kVA are required to have a 7% impedance per IEEE Std C57.12.57™-1987.

8.9 Insulation

This classification includes three types: liquid, dry, and combination. The liquid-immersed type can be further defined by the types of liquid used: mineral oil, or less-flammable liquids. Less-flammable fluid types include high-fire-point hydrocarbon fluids, silicone, or other biodegradable fluids. The dry-type includes the ventilated, cast coil, totally enclosed non-ventilated, sealed gas-filled, and vacuum pressure impregnated (VPI) types. The third classification includes a combination liquid-, vapor-, and gas-filled unit.

Dry-type transformers are being manufactured by several manufacturers with the same BIL as liquid-immersed transformers. A choice may be considered of specifying either the same BIL for dry-type as for liquid-immersed types since they both are subject to the same environment as far as impulses and transients are concerned, or providing the power system with additional surge protection. Even though both dry and liquid-immersed transformers may be specified with the same BIL ratings, in severe environments having high levels of moisture or dirt, the sealed enclosure of the liquid-immersed (or the sealed or gas-filled dry) will maintain insulation levels better and with less maintenance.

8.9.1 Insulation medium

The selection of the insulation medium is dictated mainly by the installation site and cost. For outdoor installations, the mineral-oil-insulated transformer has widespread use due to its lowest cost and inherent weatherproof construction. When located close to combustible buildings, safeguards are required as specified by the NEC, Section 450.27. For indoor installations, refer to the NEC, Section 450.26.

Where mineral-oil-immersed transformers are installed, it may be necessary to provide means to prevent any escaped oil, including drips, from migrating into the environment.

The discontinuance of the use of PCB (polychlorinated biphenyls) liquid-immersed transformers to meet regulatory requirements has promoted the use of high-fire-point liquids, such as polyalpha olefins, silicones, and high-molecular-weight hydrocarbons. They are being used in applications previously applied to PCB transformers with the tacit approval of insurance and safety authorities, as specified in the NEC®, Section 450.23. In general, these high-fire-point liquids increase the cost of the transformer compared to mineral oil. These liquids should receive essentially the same care and maintenance that applies to conventional mineral-oil-immersed transformers. Per existing federal regulatory requirements, no new transformer installations may be made using PCB liquids.

Due to environmental pollution impact, the users of existing PCB-immersed transformers should consult the manufacturer of the transformer or the manufacturer of the liquid for selection as well as proper safeguards in the disposal of used liquid. All liquid-filled transformers must be properly labeled as to content, or if of unknown content, are assumed to be PCB-contaminated.

The ventilated dry-type transformer has application in industrial plants for indoor installation where floor space, weight, and regard for liquid maintenance and safeguards would be important factors. They are the recommended choice for use inside commercial buildings, although liquid-type transformers with less-flammable fluids can also be successfully applied so long as all applicable building codes have been met.

Liquid-immersed transformers are preferred to be installed outdoors, in adjacent electrical equipment buildings, or underground in transformer vaults. If installed indoors, then primary protection is recommended to be load interrupters equipped with current-limiting fuses and vault construction and ventilation to the stricter of NEC® Article 450 or utility requirements and recommendations.

The totally enclosed non-ventilated (TENV) dry-type transformer, the cast coil (where both the high- and low-voltage coils are cast), and the sealed or gas-filled dry-type transformer, although all more expensive than ventilated dry-type or mineral-oil-immersed units, are especially suitable for adverse environments, such as where dust or lint conditions exist or where subject to moisture such as sprays or controlled wash down conditions. They require little maintenance, need no fire-proof vaults, and generally have lower losses than comparable ventilated or mineral-oil-immersed units. The same applies to the high-fire-point liquid-immersed transformers; however, when they are installed in combustible buildings or areas, automatic fire-extinguishing systems or vaults are required.

Transformers over 35 000 V installed inside a building must be installed in vaults specified in B of Article 450 of the NEC®. The indoor installation of less flammable liquid-immersed transformers must meet Section 450.23 of the NEC®.

On oil-immersed transformers, a sealed-tank construction and welded cover is standard practice with manufacturers. On substation transformers, optional oil-preservation systems may be specified as follows:

a)   A gas-oil seal that consists of an auxiliary tank mounted on the transformer. This seal provides for the expansion and contraction of the transformer gas and oil without exposing the transformer oil to the atmosphere. This option is now rarely used.

b)   An automatic gas seal that maintains a constant positive nitrogen pressure within the tank. A combination regulating valve and pressure relief operates with a cylinder of high-pressure nitrogen to control the proper functioning of this seal.

8.10 Accessories

Accessories furnished with the transformer include those identified as standard and optional in manufacturers' publications. The standard devices will vary with different types of transformers. Some of the optional devices that offer protective features include the following:

a)   Winding temperature equipment in addition to the standard top-oil temperature indicator. This device is calibrated for use with specific transformers and automatically takes into account the hottest spot temperature of the windings, ambient temperature, and load cycling. For this reason, it provides a more accurate, continuous, and automatic measure of the transformer loading and overloading capacity. It may have contacts that can be set to alarm and even subsequently trip a circuit breaker or fusible disconnect equipped with shunt trip capabilities. For all dry-type transformers, similar winding temperature protective devices employing detectors embedded in the windings are available.

b)   The pressure relay for sensitive high-speed indication of liquid-immersed transformer internal faults. Since the device is designed to operate on the rate of change of internal pressure, it is sensitive only to that resulting from internal faults and not to pressure changes due to temperature and loading.

c)   Alarm contacts such as temperature indicators, liquid-level and pressure vacuum gauges, and pressure-relief activator and alarm devices, can be included on the standard devices for more effective utilization.

d)   Surge arresters mounted directly on the transformer tank provide maximum surge protection for the transformer. The type of arrester specified and its voltage rating should be coordinated with the voltage parameters of the system on which it is applied and the BIL of the transformer. Refer to IEEE Std 141™-1993 (*IEEE Red Book™*), Chapter 6 for a detailed discussion of surge arrester application.

8.11 Termination facilities

Termination facilities are available to accommodate most types of installation. For the unit substation arrangement, indoors or outdoors, the incoming and outgoing bushings are usually side-wall-mounted and enclosed in a throat or transition section for connection to adjacent switchgear assemblies. Tank-wall-mounted enclosures, oil- or air-insulated, with or without potheads or cable clamps, are available for direct cable termination. The size and number of conductors should be specified, along with minimum space for stress cone termination, if required. For the substation-type transformers in an outdoor installation, cover-mounted bushings provide the simplest facility for overhead lines.

8.12 Sound levels

The transformer sound level is of importance in certain installations. The maximum standard levels are listed in NEMA TR 1-1993. These can be reduced to some extent by special design. The transformer manufacturer should be consulted regarding the possible reduction for a particular type and rating.

Transformer sound levels need to be addressed during the design and specification of the facility. Technical specifications can require transformer sound levels to be less than listed in industry tables. The effects of transformer sound levels can be minimized by:

 a) Installing the transformer in a room in which the walls, floors, and ceiling are massive enough to reduce the noise to a person listening on the other side.

 b) Avoid installing the transformer in a corner.

 c) Do not make any reflecting surface coincident with a half-wavelength of the frequency. For a 60 Hz transformer, the wavelength determined from c/(2 × f) where c is equal to the speed of sound (344.4 m/s) and f is the frequency (60 Hz). The result is 2.87 m, and a half-wavelength is 1.435 m. It should be noted that the speed of sound varies with temperature and relative humidity: 331.45 m/s at 0 °C and 0% RH to 351.48 m/s at 30 °C and 100% RH. If a noise hits a reflecting surface at these dimensions, then standing waves are produced that will produce reverberations (echoes). Applying absorbent materials to the walls is then necessary for sound attenuation.

 d) Flexible connections are recommended for any attachments to the transformer.

 e) Avoiding direct attachment of transformers to structural members.

8.13 Transformer heating due to harmonic currents

Transformers serving linear loads have heat losses related to their operation at the fundamental frequency of the power system. There are the typically expected power losses due to I^2R in all of the current paths, and hysteresis plus eddy-current losses within the windings, the core, and any metallic items that stray flux can engage. However, the same linear-load-rated transformer serving nonlinear (typically electronic) loads will generally exhibit increased internal heating due to several factors. (See 8.8 for the equivalent circuit for a transformer; it may be helpful to review this subclause if not already familiar with the data.)

The first factor that can increase the internal heating of the transformer has to do with I^2R losses. The typical three-phase 480 Y-120 Y/208 V distribution transformer is connected delta-wye. As shown in 4.5.3.1 of IEEE Std 1100™-2005 (*IEEE Emerald Book*™), the triplen (third and multiples of the third) harmonic components of each phase are in phase with each other. In addition to the increased neutral current, this factor also affects the primary winding of the transformer.

In order to have a current flow in the secondary of a transformer, it must have a proportional current flow in the primary. This proportion is the transformer's turns ratio, shown in Equation (14):

$$\text{turns ratio} = \frac{\text{primary winding turns}}{\text{secondary winding turns}} = \frac{V_p}{V_s} = \alpha \qquad (14)$$

If the other losses of the transformer are neglected, and only the load component of primary current (I primary) is used [see Equation (15)]:

$$\frac{I_{\text{primary}}}{I_{\text{secondary}}} = \alpha = \text{turns ratio} \qquad (15)$$

In the case of a delta-wye transformer, as seen in Figure 24, the third harmonic current on the secondary of A phase, B phase, and C phase are all in phase with each other, so they add at the neutral and all three currents flow back on the neutral.
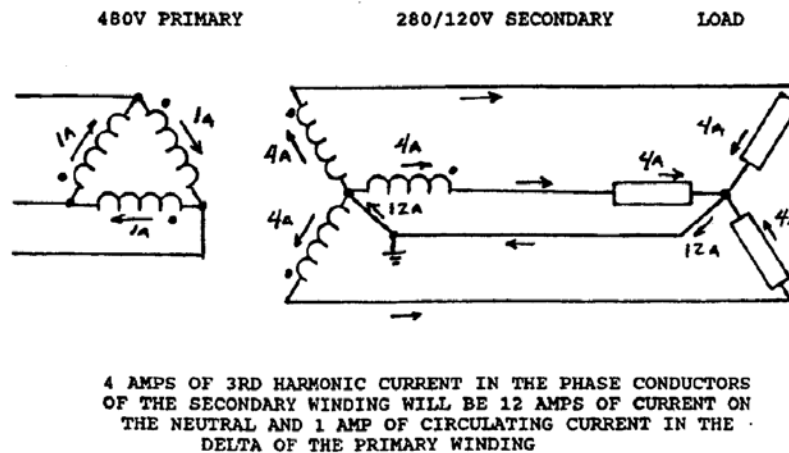

Figure 24 —Circulating third harmonic current in the delta winding

In order for the third harmonic current (or any current for that matter) to flow in the secondary of the transformer, a current must flow in the primary of the transformer equal to the secondary current divided by the turns ratio. With a delta-wye transformer, this third harmonic current will circulate around the delta. This increases the heat loss (I^2R) of the primary.

Another and often more significant factor in which harmonically distorted currents increase the internal heating of a transformer is the generation of eddy currents (the stray currents that are induced in the windings and iron core due to imperfections of the magnetic circuit). Depending on the wave shape of the current, the increased heating due to eddy-current losses can be far greater than the I^2R losses of circulating currents.

When harmonic current flows through the transformer's windings, it generates magnetic flux at each of the harmonic frequencies (h), with the flux's intensity being in proportion to the current at each frequency. Up to about the 15th harmonic, this flux produces exponential eddy-current heat losses per h^2 wherever it can engage a metallic item with significant cross-sectional area. At the highest harmonic frequencies, the relationship is no longer exponential, but is inverse, and defined by $1/h$. Between the two limits, it is fairly linear and about equal to h.

The foregoing heat losses in the transformer are in addition to those losses already expected from the action of the current flows at the fundamental frequency. I^2R ac losses due to skin effect also play a role at higher frequencies and with large diameter conductors, but the losses associated with skin effects are generally not considered to be very significant in most power transformer applications and over the most common ranges of harmonics.

An applied primary voltage containing harmonic distortion can also cause additional losses in the transformer; but in most practical cases, the harmonic current-related winding losses related to the application of nonlinear loading are the major limiting factor for transformer capacity.

8.13.1 De-rating conventional (no K-factor) transformers

At the present time, there are far more transformers in service that do not have assigned K-factor rating than transformers that do. Most of these transformers have been providing service quite adequately. This does not negate the fact that harmonic distortion causes increased heating in transformers. It brings two

additional factors to the forefront; most of the transformers currently in service are operating significantly below their nameplate rating, and technology is changing, which many of the existing facilities have not been able to keep up with.

When the nature of the loads on an existing installation has significantly changed, a reevaluation of the installation is in order. A common example is when a transformer is supplying lighting loads comprised of florescent tube lights with magnetic ballasts, and the magnetic ballasts are removed and retrofitted with electronic ballasts. Depending on the design of the electronic ballast, it could significantly increase (or decrease, for the more advanced designs) the harmonic distortion of the current it draws. Another example is when a significant amount of electronic equipment has been added (i.e., in a hospital, office building, or testing laboratory). The transformer, though only partially loaded, may be subjected to significant additional heat. The performance of the existing transformer should be evaluated with the new loads.

Typical nationally recognized testing laboratory (NRTL) listed transformers that are not K-factor rated (by the NRTL) to be used with nonlinear loads are generally restricted to use on circuits with the following characteristics, which are specified by IEEE Std C57.12.00™ (for liquid-immersed) and IEEE Std C57.12.01™ (for dry-type) transformers:

a) Approximately sinusoidal, balanced input voltage, and

b) Full-load current that does not exceed 5.0% of total harmonic distortion

These limitations are primarily due to eddy currents induced in both the windings and structural components that increase losses and can cause overheating, as previously discussed.

If acceptable to the electrical safety inspection authority having jurisdiction at the location, a conventional NRTL-listed power transformer can be de-rated so that it may serve nonlinear loads. The clear need to obtain permission for the de-rating is necessary since typical power and general-purpose dry-type transformers listed under UL 1561-2011[9] are not evaluated by the NRTL conducting the tests per the following:

"Transformers covered under this category have only been evaluated for use on sinusoidal supply circuits. They have not been investigated for use where a significant nonsinusoidal content is present such as that which may occur with uninterruptible power supplies (sic), data processing equipment, and solid state motor speed controllers." (See UL 1561).

Subsequent to obtaining permission from the electrical safety inspection authority having jurisdiction at the location, the recommended practice for establishing the losses in conventional transformers in applications where nonsinusoidal load currents are present is provided in IEEE Std C57.110™-2008. The recommended practice applies the results of studies that found winding eddy-current loss, P_{ec}, to be approximately proportional to the square of the rms load current at that harmonic, I_h, and the square of the harmonic number, h (see Crepaz [B57]).

9. Cable systems

The primary function of cable is to carry energy reliably between source and utilization equipment. In carrying this energy, there are heat losses generated in the cable that must be dissipated. The ability to dissipate these losses depends on how the cables are installed, and this affects their ratings.

Cables may be installed in raceway, in cable trays, underground in duct or direct buried, in cable bus, as open runs of cable, or may be messenger supported.

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[9] Covers air-cooled, dry-type transformers of 600 V ac and 500 kVA for 1 φ and 1500 kVA for 3 φ units.

The selection of conductor size requires consideration of the load current to be carried and the loading cycle, emergency overloading requirements and duration, fault clearing time and interrupting capacity of the cable overcurrent protection or source capacity, voltage drop, and ambient temperatures for the particular installation conditions. Caution must be exercised when locating conductors in high ambient heat areas so that the operating temperature will not exceed that designated for the type of insulated conductor involved.

Insulations can be classified in broad categories as solid insulations, taped insulations, and special purpose insulations. Cables incorporating these insulations cover a range of maximum and normal operating temperatures and exhibit varying degrees of flexibility, fire resistance, and mechanical and environmental protection.

The installation of cables requires care in order to avoid excessive pulling tensions that could stretch the conductor or insulation shield, or rupture the cable jacket when pulled around bends. The minimum bending radius of the cable or conductors should not be exceeded during pulling around bends, at splices, and particularly at terminations to avoid damage to the conductors. The engineer should also check each run to ensure that the conductor jamming ratio is correct and the maximum allowable sidewall pressure is not exceeded.

Provisions should be made for the proper terminating, splicing, and grounding of cables. Minimum clearances must be maintained between phases and between phase and ground for the various voltage levels. The terminating compartments should be designed and constructed to prevent condensation from forming. Condensation or contamination on medium-voltage terminations could result in tracking over the terminal surface with possible flashover.

Many users test cables after installation and periodically test important circuits. Test voltages are usually dc of a level recommended by the cable manufacturer for the specific cable. Usually this test level is well below the dc strength of the cable, but it is possible for accidental flashovers to weaken or rupture the cable insulation due to the higher transient overvoltages that can occur from reflections of the voltage wave. IEEE Std 400™[10] provides a detailed discussion on cable testing.

The application and sizing of all cables rated up to 35 kV is governed by the NEC®. Cable use may also be covered under state and local regulations recognized by the local electrical inspection authority having jurisdiction in a particular area.

The various tables in this chapter are intended to assist the electrical engineer in laying out and understanding, in general terms, requirements for the cable system under consideration.

9.1 Cable construction

9.1.1 Conductors

The two conductor materials in common use are copper and aluminum. Copper has historically been used for conductors of insulated cables due primarily to its desirable electrical and mechanical properties. The use of aluminum is based mainly on its favorable conductivity to weight ratio (the highest of the electrical conductor materials), its ready availability, and the lower cost of the primary metal.

The need for mechanical flexibility usually determines whether a solid or a stranded conductor is used, and the degree of flexibility is a function of the total number of strands. The NEC requires conductors of No. 8 AWG and larger to be stranded. A single insulated or bare conductor is defined as a conductor, whereas an assembly of two or more insulated conductors, with or without an overall covering, is defined as a cable.

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[10] Information on references can be found in Clause 2.

Stranded conductors are available in various configurations, such as stranded concentric, compressed, compact, rope, and bunched, with the latter two generally specified for flexing service. Bunched stranded conductors consist of a number of individual strand members of the same size that are twisted together to make the required area in circular mils for the intended service. Unlike the individual strands in a concentric stranded conductor, illustrated in Figure 25, the strands in a bunch stranded conductor are not controlled with respect to one another. This type of conductor is usually found in portable cords.
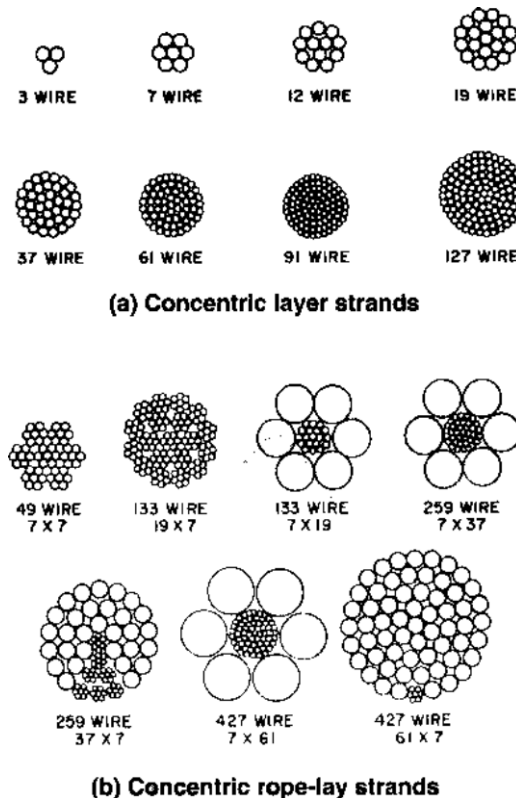

Figure 25 —Conductor stranding

9.1.2 Comparison between copper and aluminum

Aluminum requires larger conductor sizes to carry the same current as copper. For equivalent ampacity, aluminum cable is lighter in weight and larger in diameter than copper cable. The properties of these metals are given in Table 22.

The 36% difference in thermal coefficients of expansion and the different electrical nature of their oxide films require consideration in connector designs. An aluminum oxide film forms immediately on exposure of fresh aluminum surface to air. Under normal conditions it slowly builds up to a thickness of 3 nanometers (nm) to 6 nm and stabilizes at this thickness. The oxide film is essentially an insulating film or dielectric material and provides aluminum with its corrosion resistance. Copper produces its oxide rather slowly under normal conditions, and the film is relatively conducting, presenting no real problem at connections. Approved connector designs for aluminum conductors essentially provide increased contact areas and lower unit stresses than are used for copper cable connectors. These terminals should possess adequate strength to help ensure that the compression of the aluminum strands exceeds their yield strength and that a brushing action takes place that destroys the oxide film to form an intimate aluminum contact area yielding a low-resistance connection. Recently developed aluminum alloys provide improved terminating and handling as compared to electrical conductor (EC) grades.

Water should be kept from entering the strand space in aluminum conductors at all times. Any moisture within a conductor, either copper or aluminum, is likely to cause corrosion of the conductor metal or impair insulation effectiveness.

Table 22 —Properties of copper and aluminum

Property	Copper electrolytic	Aluminum EC
Conductivity, % IACS[a] at 20 °C	100.0	61.0
Resistivity, $\Omega \times$ cmil/ft at 20 °C	10.371	17.002
Specific gravity at 20 °C	8.89	2.703
Melting point, °C	1083	660
Thermal conductivity at 20 °C, (cal $\times$ cm)/(cm^2 $\times$ °C $\times$ s) [b]	0.941	0.58
Specific heat, cal/(g $\times$ °C) [b] for equal weights for equal direct-current resistance	0.092 0.184	0.23 0.23

Thermal expansion, in; equal to constant · 10-6 length in inches $\times$ °F
    Steel   =   6.1
    18-8 stainless = 10.2
    brass   = 10.5
    bronze   = 15
	9.4	12.8

Relative weight for equal direct-current resistance and length	1.0	0.50
Modulus of elasticity, (lb/in^2) $\times 10^6$	16	10

[a] International annealed copper standard.
[b] In this table, cal denotes the gram calorie.

9.1.3 Insulation

Basic insulating materials are classified as either organic or inorganic. A wide variety of insulations fall into the organic classification. Mineral-insulated cable employs the one inorganic insulation, magnesium oxide (MgO), that is generally available.

Insulations in common use are the following:

    a)   Thermosetting compounds, solid dielectric

    b)   Thermoplastic compounds, solid dielectric

    c)   Paper laminated tapes

    d)   Varnished cloth, laminated tapes

    e)   Mineral insulation, solid dielectric granular

Table 23 —Commonly used insulating materials

Common name	Chemical composition	Properties of insulation	
		Electrical	Physical
Thermosetting			
Cross-linked polyethylene	Polyethylene	Excellent	Excellent
EPR	Ethylene propylene rubber (copolymer and terpolymer)	Excellent	Excellent
Butyl	Isobutylene isoprene	Excellent	Good
SBR	Styrene butadiene rubber	Excellent	Good
Oil base	Complex rubber-like compound	Excellent	Good
Silicone	Methyl chlorosilane	Good	Good
TFE (see Note 1)	Tetrafluoroethylene	Excellent	Good
ETFE (see Note 2)	Ethylene tetrafluoroethylene	Excellent	Excellent
Neoprene	Chloroprene	Fair	Good
Class CP rubber (see Note 3)	Chlorosulfonated polyethylene	Good	Good
Thermoplastic			
Polyethylene	Polyethylene	Excellent	Good
Polyvinyl chloride	Polyvinyl chloride	Good	Good
Nylon	Polyamide	Fair	Excellent
NOTE 1—For example, Teflon® or Halon NOTE 2—For example, Tefzel® NOTE 3—For example, Hypalon®			

Most of the basic materials listed in Table 23 must be modified by compounding or mixing with other materials to produce desirable and necessary properties for manufacturing, handling, and end use. The thermosetting or rubber-like materials are mixed with curing agents, accelerators, fillers, and antioxidants in varying proportions. Cross-linked polyethylene (XLPE) is included in this class. Generally, smaller amounts of materials are added to the thermoplastics in the form of fillers, antioxidants, stabilizers, plasticizers, and pigments.

a) *Insulation comparison.* The aging factors of heat, moisture, and ozone are among the most destructive to organic insulations, so the following comparisons are a gauge of the resistance and classifications of these insulations.
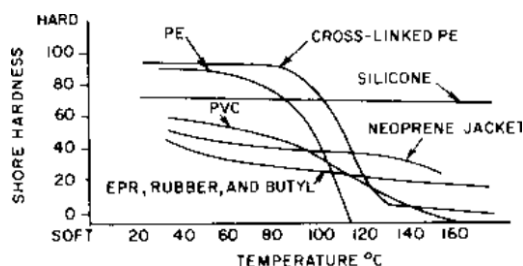

Figure 26 —Typical values for hardness versus temperature

1) *Relative heat resistance.* The comparison in Figure 26 illustrates the effect of a relatively short period of exposure at various temperatures on the hardness characteristic of the material.
2) *Heat aging.* The effect on elongation of an insulation (or jacket) when subjected to aging in a circulating air oven is an acceptable measure of heat resistance. The air oven test at 121 °C, which is contained in some specifications, is severe, but provides a relatively quick method of grading materials for possible use at elevated conductor temperatures or in hot spot areas. The 150 °C oven aging is many times more severe and is used to compare materials with superior heat resistance. The temperature ratings of insulations in general use are shown in Table 24.

Depending upon the operating conditions, the maximum shield temperature must also be considered (see ICEA P-45-482-2007).

3) *Ozone and corona resistance.* Exposure to accelerated conditions, such as higher concentrations of ozone (as standardized by NEMA WC 71-1999) for butyl, 0.03% ozone for 3 h at room temperature, or air oven tests followed by exposure to ozone, or exposure to ozone at elevated temperatures, aids in measuring the ultimate ozone resistance of the material. Insulations exhibiting superior ozone resistance under accelerated conditions are silicone, rubber, polyethylene, cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), and polyvinyl chloride (PVC). In fact, these materials are, for all practical purposes, inert in the presence of ozone. However, this is not the case with corona discharge.

The phenomenon of corona discharge produces concentrated and destructive thermal effects along with formation of ozone and other ionized gases. Although corona resistance is a property associated with cables over 600 V, in a properly designed and manufactured cable, damaging corona is not expected to be present at operating voltage. Materials exhibiting less susceptibility than polyethylene and XLPE to such discharge activity are the EPRs.

4) *Moisture resistance.* Insulations such as XLPE, polyethylene, and EPR exhibit excellent resistance to moisture as measured by standard industry tests, such as the ICEA Accelerated Water Absorption Test—Electrical Method (EM-60) (see NEMA WC 70-2009 and NEMA WC 74-2006). The electrical stability of these insulations in water as measured by capacitance and power factor is impressive. A degradation phenomenon called "treeing" has been found to be aggravated by the presence of water. This phenomenon appears to occur in solid dielectric insulations and is more prevalent in polyethylene and XLPE than in EPR. The capacitance and power factor of natural polyethylene and some cross-linked polyethylenes are lower than those of EPR or other elastomeric power cable insulations.

b) *Insulations in general use.* Insulations in general use for 2 kV and above are shown in Table 24. Solid dielectrics, both thermoplastic and thermosetting, are used most frequently, while laminated constructions, such as paper and lead cables, are being used only on critical circuits in industrial facilities.

The generic names given for these insulations cover a broad spectrum of actual materials, and the history of performance on any one type may not properly be related to another in the same generic family.

Table 24 —Rated conductor temperatures

Insulation type	Maximum voltage class (kV)	Maximum operating temperature (°C)	Maximum overload[a] temperature (°C)	Maximum short-circuit temperature (°C)
Paper (solid-type) multi-conductor and single conductor, shielded	9	95	115	200
	29	90	110	200
	49	80	100	200
	69	65	80	200
Varnished cambric	5	85	100	200
	15	77	85	200
	28	70	72	200
Polyethylene (natural)[b]	5	75	95	150
	35	75	90	150
SBR rubber	2	75	95	200
Butyl rubber	5	90	105	200
	35	85	100	200
Oil-base rubber	35	70	85	200
Polyethylene (cross-linked)[b]	35	90	130	250
EPR rubber	35	105	140	250
Chlorosulfonated polyethylenet	2	90	130	250
Polyvinyl chloride	2	60	85	150
	2	75	95	150
	2	90	105	150
Silicone rubber	5	125	150	250
Ethylene tetrafluoroethylene[c]	2	150	200	250

[a] Operation at these overload temperatures shall not exceed 100 h/yr. Such 100 h overload periods shall not exceed five.

[b] Cables are available in 69 kV and higher ratings.

[c] For example, Tefzel®.

9.1.4 Cable design

The selection of power cable for particular circuits or feeders should be based on the following considerations:

a) *Electrical.* Dictates conductor size, type and thickness of insulation, correct materials for low- and medium-voltage designs, consideration of dielectric strength, insulation resistance, specific inductive capacitance (dielectric constant), and power factor.

b) *Thermal.* Compatible with ambient and overload conditions, expansion, and thermal resistance.

c) *Mechanical.* Involves toughness and flexibility, consideration of jacketing or armoring, and resistance to impact, crushing, abrasion, and moisture.

d) *Chemical.* Stability of materials on exposure to oils, flame, ozone, sunlight, acids, and alkalies.

e) *Flame resistance.* Cables installed in cable tray must be listed by a nationally recognized testing laboratory as being flame retardant and marked for installation in cable tray. The marking may be "Type TC," "TC," "for use in cable trays," or "for CT use," depending on the voltage and construction.

f) *Low smoke.* The NEC authorizes the addition of the suffix "LS" to the cable marking on any cable construction that is flame retardant and has limited smoke characteristics. The criteria for "Limited Smoke" were being developed at the time this recommended practice was published. While the NEC® does not specifically require the use of "LS" constructions in any area, this requirement might be considered for occupancies with large populations or high-rise occupancies.

g)   *Toxicity.* All electrical wire and cable installed or terminated in any building in the State of New York after December 16, 1987 must have the toxicity level and certain other data for the product on file with the New York Secretary of State.

The installation of cable in conformance with the NEC® and state and local codes under the jurisdiction of a local electrical inspection authority requires evidence of listing for use in the intended application and occupancy by a nationally recognized testing laboratory, such as Underwriters Laboratories (UL). Some of the more common industrial types listed in the NEC® types are discussed in 9.1.4.1 through 9.1.4.4.

9.1.4.1 Low-voltage cables

Low-voltage power cables are generally rated at 600 V, regardless of the voltage used, whether 120 V, 208 V, 240 V, 277 V, 480 V, or 600 V.

The selection of 600 V power cable is oriented more toward physical rather than electrical service requirements. Resistance to forces, such as crush, impact, and abrasion becomes a predominant factor, although good electrical properties for wet locations are also needed.

The 600 V compounds of cross-linked polyethylene (XLPE) are usually filled with carbon black or mineral fillers to further enhance the relatively good toughness of conventional polyethylene. The combination of cross-linking the polyethylene molecules through vulcanization plus fillers produces superior mechanical properties. Vulcanization eliminates polyethylene's main drawback of a relatively low melting point of 105 °C. The 600 V construction consists of a copper or aluminum conductor with a single extrusion of insulation in the specified thickness.

Rubber-like insulations, such as ethylene propylene rubber (EPR) and styrene butadiene rubber (SBR), require outer jackets for mechanical protection, usually of polyvinyl chloride (PVC), neoprene, or CP rubber. However, the newer EPR insulations have improved physical properties that do not require an outer jacket for mechanical protection. A list of the more commonly used 600 V conductors and cables is provided below. Cables are classified by conductor operating temperatures and insulation thicknesses in accordance with the NEC®.

a)   EPR or XLPE insulated, with or without a jacket. Type RHW for 75 °C maximum operating temperature in wet or dry locations, Type RHH for 90 °C in dry locations only, and Type RHW-2 for 90 °C maximum operating temperature in wet and dry locations.
b)   XLPE or EPR insulated, without jacket. Type XHHW for 75 °C maximum operating temperature in wet locations and 90 °C in dry locations only, and Type XHHW-2 for 90 °C maximum operating temperature in wet and dry locations.
c)   PVC insulated, nylon jacketed. Type THWN for 75 °C maximum operating temperature in wet or dry locations, and Type THHN for 90 °C in dry locations only.
d)   PVC insulated, without jacket. Type THW for 75 °C maximum operating temperature in wet or dry locations.
        The preceding conductors are suitable for installation in conduit, duct, or other raceway, and, when specifically approved for the purpose, may be installed in cable tray (1/0 AWG and larger) or direct-buried, provided NEC® requirements are satisfied.
        Cables in items b) and d) are usually restricted to conduit or duct. Single conductors may be furnished paralleled or multiplexed, as multi-conductor cables with an overall nonmetallic jacket or as aerial cable on a messenger.
e)   Metal-clad cable, Type MC. A multi-conductor cable employing either an interlocking tape armor or a continuous metallic sheath (corrugated or smooth), with or without an overall jacket. The maximum temperature rating of the cable is based upon the temperature rating of the individual insulated conductors used, which are usually Type XHHW, XHHW-2, RHH/RHW, or RHW-2. Type MC cable may be installed in any raceway, in cable tray, as open runs of cable, direct buried, or as aerial cable on a messenger.

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f) Power and control tray cable, Type TC. A multi-conductor cable with an overall flame-retardant nonmetallic jacket. The individual conductors may be any of the above and the cable has the same maximum temperature rating as the conductors used. Type TC may be installed in cable trays, raceways, or where supported in outdoor locations by a messenger wire.

Note that the temperatures listed are the maximum rated operating temperatures as specified in the NEC®.

9.1.4.2 Power-limited circuit cables

When the power in the circuit is limited to the levels defined in Article 725 of the NEC® for remote-control, signaling, and power-limited circuits, then Class 2 (CL2) or Class 3 (CL3) power-limited circuit cables or power-limited tray cable (Type PLTC) may be utilized as the wiring method. These cables, which are rated 300 V, include copper conductors for electrical circuits and thermocouple alloys for thermocouple extension wire.

Cables installed in ducts, plenums, and other spaces used for environmental air must be plenum cable Type CL2P or CL3P. Cables installed in vertical runs and penetrating more than one floor, or cables installed in vertical runs in a shaft must be riser cable Type CL2R or CL3R. Limited-use Type CL2X or CL3X cables may be installed in dwellings or in raceway in buildings. Cables installed in cable tray must be Type PLTC.

If the circuit is not Class 2 or Class 3 power-limited, then 600 V branch circuit conductors or cable must be used.

Similarly, power-limited fire-protective signaling circuit cable may be used on circuits that comply with the power limitations of Article 760 of the NEC. Type FPLP cable is required for plenums, Type FPLR cable for risers, and Type FPL cable for general-purpose fire alarm use. If the circuit is not power-limited, then 600 V cables must be used. Type NPLFP cable is required for plenums, Type NPLFR cable for risers, and Type NPLF cable for general-purpose fire alarm use.

9.1.4.3 Medium-voltage cables

Type MV (medium-voltage) power cables have solid extruded dielectric insulation and are rated from 2001 V to 35 000 V. These single conductor and multi-conductor cables are available with nominal voltage ratings of 5 kV, 8 kV, 15 kV, 25 kV, and 35 kV. Solid dielectric 69 kV and 138 kV transmission cables are also available, however, they are not listed in the NEC®.

EPR and XLPE are the usual insulating compounds for Type MV cables; however, polyethylene and butyl rubber are also available. The maximum operating temperatures are 105 °C for EPR, 90 °C for XLPE, 85 °C for butyl rubber, and 75 °C for polyethylene.

Type MV cables may be installed in raceways in wet or dry locations. The cable must be specifically listed for installation in cable tray, direct burial, exposure to sunlight, exposure to oils, or for messenger-supported wiring.

Multi-conductor Type MV cables that also comply with the requirements for Type MC metal-clad cables may be labeled as Type MV or MC and may be installed as open runs of cable.

9.1.4.4 Shielding of medium-voltage cable

For operating voltages below 2 kV, non-shielded constructions are normally used. Above 2 kV, cables are required to be shielded to comply with the NEC® and ICEA standards. The NEC® does permit the use of non-shielded cables up to 2.4 kV provided the conductors are listed by a nationally recognized testing

laboratory and are approved for the purpose. Where non-shielded conductors are used in wet locations, the insulated conductor(s) must have an overall nonmetallic jacket or a continuous metallic sheath, or both. Refer to the NEC® for specific insulation thicknesses for wet or dry locations. The NEC® also requires non-shielded conductors to be provided with an insulation resistant to electric discharge and surface tracking, or the insulated conductor(s) shall be covered with a material resistant to ozone, electric discharge, and surface tracking. Insulation and jacket thickness must comply with the requirements of NEC® Table 310.13(D). The NEC® also allows the use of non-shielded direct-buried conductors on series connected airfield lighting circuits rated up to 5 kV and powered by a regulator. The engineer should refer to Federal Aviation Administration (FAA) Advisory Circulars (AC) for further details on their requirements and practices.

Since shielded cable is usually more expensive than non-shielded cable, and the more complex terminations require a larger terminal box, non-shielded cable has been used extensively at 2400 V and 4160 V and occasionally at 7200 V. However, any of the following conditions may dictate the use of shielded cable:

a)   Personnel safety

b)   Single conductors in wet locations

c)   Direct earth burial

d)   Where the cable surface may collect unusual amounts of conducting materials (e.g., salt, soot, conductive pulling compounds)

Shielding of an electric power cable is commonly referred to as the practice of confining the electric field of the cable to the insulation surrounding the conductor by means of conducting or semiconducting layers, or both, which are in intimate contact or bonded to the inner and outer surfaces of the insulation. In other words, the outer insulation shield confines the electric field to the space between the conductor and the shield. The inner or strand stress relief layer is at or near the conductor potential. The outer or insulation shield is designed to carry the charging currents and, in many cases, fault currents. The conductivity of the shield is determined by its cross-sectional area and the resistivity of the metal tapes or wires employed in conjunction with the semiconducting layer.

The metallic shield, which is available in several forms, is an electrostatic shield and is not designed to carry fault currents. The most common is the tape shield consisting of a copper tape, 3 mils to 5 mils thick, which is helically applied over the insulation shield.

A modification of the tape shield consists of a corrugated copper tape applied longitudinally over the insulation shield. This permits full electrical use of the tape as a current-carrying conductor, and it is capable of carrying a much greater fault current than a helically wrapped tape.

Another type is a wire shield, where copper wires are helically applied over the insulation screen with a long lay. The cross sectional area of a wire shield can vary anywhere from 15% to 20% less than the cross-sectional area of a tape shield to several times the cross-sectional area of a tape shield. Cables with wire shields tend to have higher cost than cables with taped shields, but the larger cross sectional area the wire shield can provide can make the shield better able to survive fault currents and provide better reliability. Wire shields may be less susceptible to corrosion caused by cable jacket damage that can increase the effective resistance of the shield and force currents to flow in a helical pattern rather than as a longitudinal straight line along the conductor.

A modification of the wire shielding system consists of six corrugated copper drain wires embedded in an extruded black conducting chlorinated polyethlene (CPE) combination insulation shield and jacket.

An extruded lead sheath may also be used as a combination shield and mechanical covering. The thickness of the lead can be varied to provide the desired cross-sectional area to carry the required fault current. The lead also provides an excellent moisture barrier for direct burial applications.

The stress-control layer at the inner and outer insulation surfaces, by its close bonding to the insulation surface, presents a smooth surface to reduce the stress concentrations and minimize void formation. Ionization of the air in such voids can progressively damage insulating materials and eventually cause failure.

Insulation shields have several purposes:

   a)   To confine the electric field within the cable

   b)   To equalize voltage stress within the insulation, minimizing surface discharges

   c)   To protect cable from induced potentials

   d)   To limit electromagnetic or electrostatic interference to communications receivers (e.g., radio, TV)

   e)   To reduce shock hazard (when properly grounded)

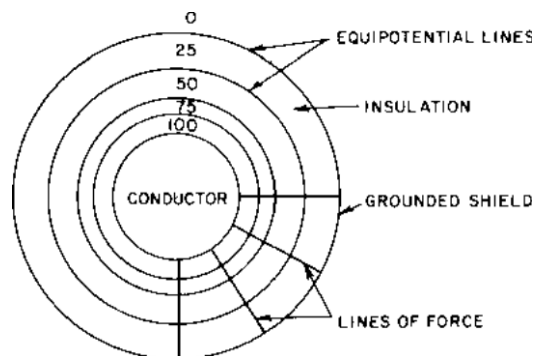Figure 27 illustrates the electrostatic field of a shielded cable.

Figure 27 —Electric field of shielded cable

The voltage distribution between a non-shielded cable and a grounded plane is illustrated in Figure 28. Here, it is assumed that the air is the same, electrically, as the insulation, so that the cable is in a uniform dielectric above the ground plane to permit a simpler illustration of the voltage distribution and field associated with the cable.

In a shielded cable (see Figure 27), the equipotential surfaces are concentric cylinders between conductor and shield. The voltage distribution follows a simple logarithmic variation, and the electrostatic field is confined entirely within the insulation. The lines of force and stress are uniform and radial and cross the equipotential surfaces at right angles, eliminating any tangential or longitudinal stresses within the insulation or on its surface.
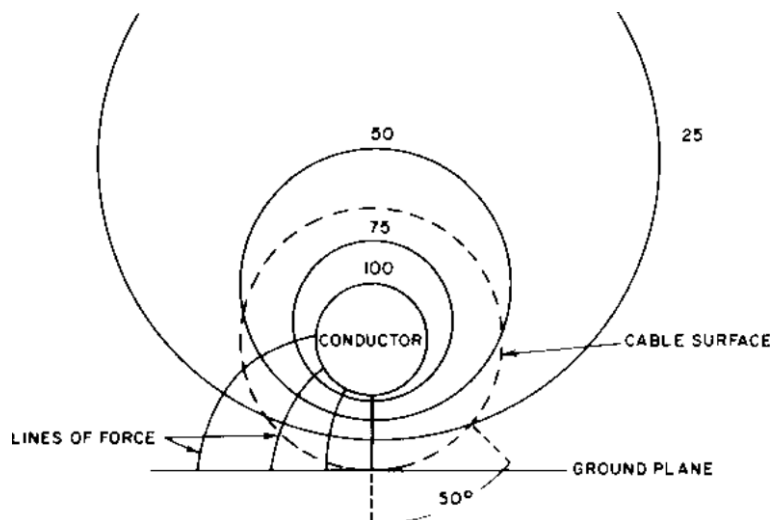
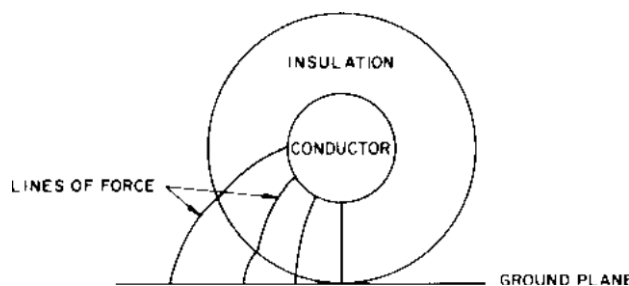**Figure 28 —Electric field of conductor on ground plane in uniform dielectric**

Figure 29 —Electric field of non-shielded cable on ground plane

The equipotential surfaces for the non-shielded system (see Figure 29) are cylindrical but not concentric with the conductor and cross the cable surface at many different potentials. The tangential creepage stress to ground at points along the cable may be several times the normal recommended stress for creepage distance at terminations in dry locations for non-shielded cable operating on 4160 V systems.

Surface tracking, burning, and destructive discharges to ground could occur under these conditions. However, properly designed non-shielded cables, as described in the NEC®, limit the surface energies available, which could protect the cable from these effects.

Typical cables supplied for shielded and non-shielded applications are illustrated in Figure 30.

9.2 Cable outer finishes

Cable outer finishes or outer coverings are used to protect the underlying cable components from the environmental and installation conditions associated with the intended service. The choice of a cable outer finish for a particular application is based on the same performance criteria as used for insulations, namely electrical, thermal, mechanical, and chemical. A combination of metallic and nonmetallic coverings are available to provide the total protection needed for the particular installation and operating conditions. Specific industry requirements for these coverings are defined in IEEE, UL, ICEA, and ASTM standards.

9.2.1 Nonmetallic finishes

a) *Extruded jackets.* There are outer coverings, either thermoplastic or vulcanized, that may be extruded directly over the insulation, or over electrical shielding systems of metal sheaths or tapes, copper braid, or semiconducting layers with copper drain wires or spiraled copper concentric wires, or over multi-conductor constructions. Commonly used materials include polyvinyl chloride (PVC), chlorinated polyethylene (CPE), nitrile butadiene/polyvinyl chloride (NBR/PVC), cross-linked polyethylene (XLPE), polychloroprene (neoprene), and chlorosulfonated polyethylene (hypalon). While the detailed characteristics may vary due to individual manufacturers' compounding, these materials provide a high degree of moisture, chemical, and weathering protection, are reasonably flexible, provide some degree of electrical isolation, and are of sufficient mechanical strength to protect the insulating and shielding components from normal service and installation damage. Materials are available for service temperatures from -55 °C to +115 °C.

b) *Fiber braids.* This category includes braided, wrapped, or served synthetic or natural fiber materials selected by the cable manufacturer to best meet the intended service. While asbestos fiber has been the most common material used in the past, fiberglass is now used extensively for employee health reasons. Some special industrial applications may require synthetic or cotton fibers applied in braid form. All fiber braids require saturants or coating and impregnating materials to provide some degree of moisture and solvent resistance as well as abrasive and weathering resistance.

Glass braid is used on cables to minimize flame propagation, smoking, and other hazardous or damaging products of combustion.
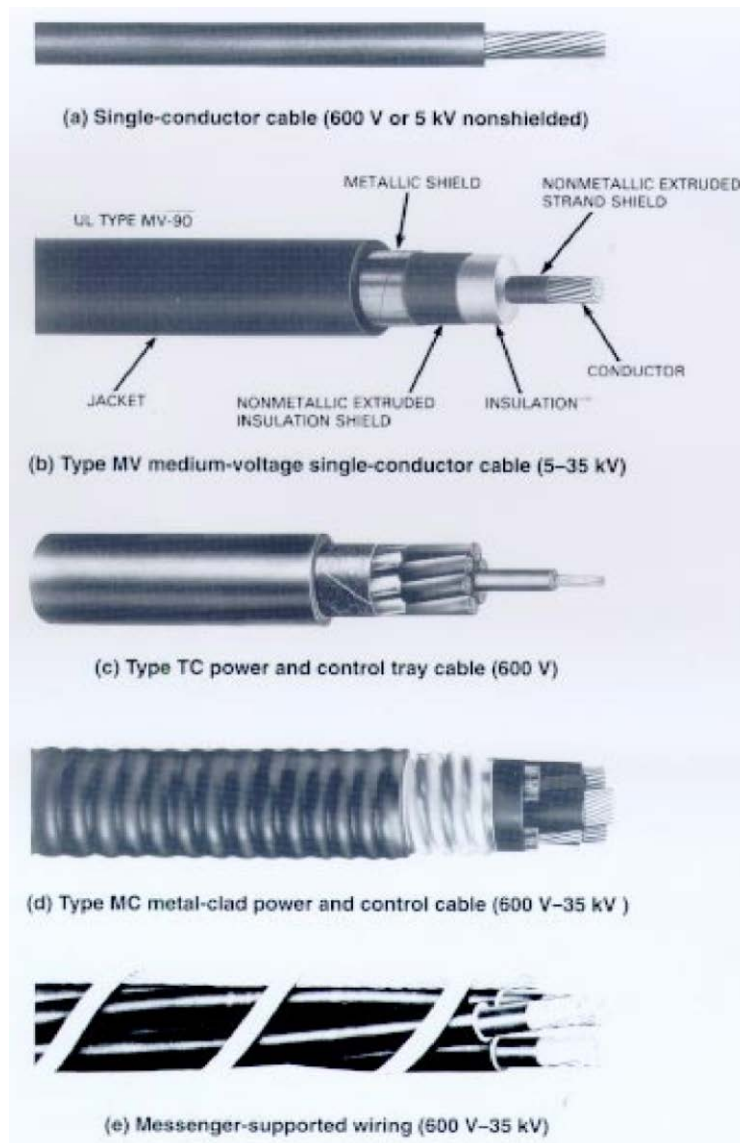
(a) Single-conductor cable (600 V or 5 kV nonshielded)

(b) Type MV medium-voltage single-conductor cable (5–35 kV)

(c) Type TC power and control tray cable (600 V)

(d) Type MC metal-clad power and control cable (600 V–35 kV)

(e) Messenger-supported wiring (600 V–35 kV)

Figure 30 —Commonly used shielded and non-shielded constructions

9.2.2 Metallic finishes

This category of materials is widely used where a high degree of mechanical, chemical, or short-time thermal protection of the underlying cable components is required by the application. Commonly used materials are interlocked galvanized steel, aluminum, or bronze armor; extruded lead or aluminum; longitudinally applied, welded, and corrugated aluminum or copper sheath; and helically applied round or flat armor wires. The use of any of these materials, alone or in combination with others, does reduce flexibility of the overall cable.

Installation and operating conditions may involve localized compressive loadings, occasional impact from external sources, vibration and possible abrasion, heat shock from external sources, extended exposure to corrosive chemicals, and condensation.

a) *Interlocked armor*. Provides mechanical protection with minimum reduction in flexibility. While not entirely impervious to moisture or corrosive agents, interlocked armor does provide mechanical protection

against impact and abrasion and protection from thermal shock by acting as a heat sink for short periods of localized exposure.

When moisture protection is required, an inner jacket over the cable core and under the armor is required. If an inner jacket is not used, 600 V cables in wet locations can be rated for only 75 °C unless the newer RHW-2 or XHHW-2 conductors are used, in which case the cable can then be rated 90 °C wet or dry.

Where corrosion resistance is required for either environmental conditions, direct burial, or embedment in concrete, an overall jacket is required.

The use of interlocked galvanized steel armor should be avoided on single-conductor ac power circuits due to the high hysteresis and eddy current losses. This effect, however, is minimized by using three conductor cables with overall armor or with aluminum armor on single-conductor cables.

Commonly used interlocked armor materials are galvanized steel, aluminum (for less weight and corrosion resistance), marine bronze, and other alloys for highly corrosive atmospheres.

b) *Corrugated metal sheath.* Longitudinally welded and corrugated metal sheaths (corrugations formed perpendicular to the cable axis) have been used for many years in direct buried communications cables, but only since 1960 has this method of cable core protection been applied to control and power cable. The sheath material may be of copper, aluminum, copper alloy, or a bimetallic composition with the choice of material selected to best meet the intended service.

The corrugated metal sheath offers mechanical protection equal to or greater than interlocked armor but at a lower weight. The aluminum or copper sheath may also be used as the equipment grounding conductor, either alone or in parallel with a grounding conductor within the cable.

The sheath is made from a metal strip that is longitudinally formed around the cable, welded into a continuous, impervious metal cylinder, and corrugated for pliability and increased radial strength. This sheath offers maximum protection from moisture and liquid or gaseous contaminants. An extruded nonmetallic jacket must be used over the metal sheath for direct burial, embedment in concrete, or in areas that are corrosive to the metal sheath. This cable construction is typically rated 90 °C in wet or dry locations.

c) *Lead.* Pure or lead alloy is occasionally used for power cable sheaths for moisture protection in underground manhole and tunnel, or underground duct distribution systems subject to flooding. While not as resistant to crushing loads as interlocked armor or a corrugated metal sheath, its very high degree of corrosion and moisture resistance makes lead attractive in these applications. Protection from installation damage can be provided by an outer jacket of extruded material.

Pure lead is subject to work hardening and should not be used in applications where flexing may be involved. Copper- or antimony-bearing lead alloys are not as susceptible to work hardening as pure lead, and may be used in applications involving limited flexing. Lead or its alloys must never be used for repeated flexing service.

One problem encountered today with the use of lead sheathed cable is in the area of splicing and terminating. Installation personnel experienced in the art of wiping lead sheath joints are not as numerous as they were many years ago, which poses an installation problem for many potential users. However, many insulation systems do not require lead sleeves at splices and treat the lead like any other metallic sheath.

d) *Aluminum or copper.* Extruded aluminum or copper sheaths, or die-drawn aluminum or copper sheaths, are used in certain applications for weight reduction and moisture penetration protection. While more crush-resistant than lead, aluminum sheaths are subject to electrolytic attack when installed

underground. Under these conditions, aluminum sheathed cable should be protected with an extruded outer jacket.

Mechanical splicing sleeves are available for use with aluminum-sheathed cables, and sheath joints can be made by inert gas welding, provided that the underlying components can withstand the heat of welding without deterioration. Specifically designed hardware is available for terminating the sheath at junction boxes and enclosures.

e) *Wire armor.* Significant mechanical protection and particularly longitudinal strength can be obtained with the use of spirally wrapped or braided round steel armor wire. This type of outer covering is frequently used in submarine cable and vertical riser cable for mechanical protection and support. As noted for steel interlocked armor, this form of protection should be used only on three conductor power cables to minimize sheath losses.

9.2.3 Single- and multi-conductor constructions

Single-conductor cables are usually easier to handle and can be furnished in longer lengths as compared to multi-conductor cables. The multi-conductor constructions have smaller overall dimensions than the same number of single-conductor cables, which can be an advantage where space is important.

Sometimes the outer finish can influence whether the cable should be supplied as a single- or multi-conductor cable. For example, as mentioned previously, the use of steel interlocked or steel wire armor on ac cables is practical on multi-conductor constructions, but should be avoided on single-conductor cables. It is also more economical to apply a metallic sheath or armor over multi-conductor constructions rather than over each of the single-conductor cables.

Table 25 —Properties of jackets and braids

Material	Abrasion resistance	Flexibility	Low temperature	Heat resistance	Fire resistance
Neoprene	Good	Good	Good	Good	Good
Class CP rubber[a]	Good	Good	Fair	Excellent	Good
Cross-linked polyethylene	Good	Poor	Poor	Excellent	Poor
Polyvinyl chloride	Fair	Good	Fair	Good	Fair
Polyurethane	Excellent	Good	Good	Good	Poor
Glass braid	Fair	Good	Good	Excellent	Excellent
Nylon	Excellent	Fair	Good	Good	Fair
ETFE	Excellent	Poor	Excellent	Good	Fair

[a]For example, Hypalon®.

NOTE—Chemical resistance and barrier properties depend on the particular chemicals involved, and the question should be referred to the cable manufacturer.

9.2.4 Physical properties of materials for outer coverings

Depending on the environment and application, the selection of outer finishes to provide the degree of protection needed can be complex. For a general appraisal, Table 25 lists the relative properties of some commonly used materials.

9.3 Cable ratings

9.3.1 Voltage rating

The selection of the cable insulation (voltage) rating is made on the basis of the phase-to-phase voltage of the system in which the cable is to be applied, whether the system is grounded or ungrounded, and the time in which a ground fault on the system is cleared by protective equipment. It is possible to operate cables on ungrounded systems for long periods of time with one phase grounded due to a fault. This results in line-to-line voltage stress across the insulation of the two ungrounded conductors. Therefore, such cable must have greater insulation thickness than a cable used on a grounded system where it is impossible to impose full line-to-line potential on the other two unfaulted phases for an extended period of time.

Therefore, 100% insulation level cables are applicable to grounded systems provided the protection devices will clear ground faults within 1 min. On ungrounded systems where the clearing time of the 100% level category cannot be met, yet there is adequate assurance that the faulted section will be cleared within 1 h, 133% insulation level cables are required. On systems where the time required to de-energize a grounded section is indefinite, a 173% insulation level is used.

9.3.2 Conductor selection

The selection of conductor size is based on the following considerations:

a) Load current criteria as related to loadings, the NEC® requirements, thermal effects of the load current, mutual heating, losses produced by magnetic induction, and dielectric losses

b) Emergency overload criteria

c) Voltage drop limitations

d) Fault current criteria

e) Frequency criteria

f) Hot-spot temperature criteria

g) Length of cable in elevated ambient temperature areas

h) Equipment termination requirements

i) Load current criteria

The ampacity tables in the NEC® for low- and medium-voltage cables must be used where the NEC® applies. These are derived from IEEE S-135.

All ampacity tables show the minimum conductor size required, but conservative engineering practice, future load growth considerations, voltage drop, and short-circuit heating may make the use of larger conductors necessary.

Large groups of cables should be carefully considered, as de-ratings due to mutual heating may be limiting. Conductor sizes over 500 kcmil require the consideration of paralleling two or more smaller size cables because the current-carrying capacity per circular mil of conductor decreases for ac circuits due to skin effect and proximity effect. The reduced ratio of surface to cross-sectional area of the larger conductors is a factor in the reduced ability of the larger conductor to dissipate heat. When multiple cables are used, consideration must be given to the phase placement of the cables to minimize the effects of maldistribution of current in the cables, which will also reduce ampacity. Although the material cost of cable may be less for two smaller conductors, this cost saving may be offset by increased installation costs.

The use of load factor in underground runs takes into account the heat capacity of the duct bank and surrounding soil that responds to average heat losses. The temperatures in the underground section will follow the average loss, thus permitting higher short-period loadings. The load factor is the ratio of average load to peak load. The average load is usually measured on a daily basis; the peak load is the average of a 30 min to 1 h period of the maximum loading that occurs in 24 h.

For direct buried cables, the average cable surface temperature is limited to 60 °C to 70 °C, depending on soil conditions, to prevent moisture migration and thermal runaway.

Cables must be de-rated when in proximity to other loaded cables or heat sources, or when the ambient temperature exceeds the ambient temperature on which the ampacity (current-carrying capacity) tables are based.

The normal ambient temperature of a cable installation is the temperature the cable would assume at the installed location with no load being carried on the cable. A thorough understanding of this temperature is required for a proper determination of the cable size required for a given load. For example, the ambient temperature for a cable exposed in the air and isolated from other cables is the temperature of that cable before load is applied, assuming, of course, that this temperature is measured at the same time of day and with all other conditions exactly the same as they will be when the required load is being carried. It is also assumed that, for cables in air, the space around the cable is large enough so that the heat generated by the cable can be dissipated without raising the temperature of the room as a whole. Unless exact conditions are specified, the following ambients are commonly used for calculation of current-carrying capacity.

a) *Indoors.* The ampacity tables in the NEC® are based upon an ambient temperature of 30 °C for low-voltage cables. In most parts of the United States, 30 °C is too low for summer months, at least for some parts of the building. The Type MV cable ampacity tables in the NEC are based upon a 40 °C ambient air temperature. In any installation where the conditions are accurately known, the measured temperature should be used; otherwise, use 40 °C. Refer to NEC® Article 392 for cables installed in cable tray.

Sources of heat adjacent to the cables under the most adverse condition should be taken into consideration when calculating the current-carrying capacity. This is usually done by correcting the ambient temperature for localized hot spots. These may be caused by steam lines or other heat sources adjacent to the cable, or they may be due to sections of the cable running through boiler rooms or other hot locations. Rerouting may be necessary to avoid this problem.

b) *Outdoors.* An ambient temperature of 40 °C is commonly used as the maximum for cables installed in the shade and 50 °C for cables installed in the sun. In using these ambient temperatures, it is assumed that the maximum load occurs during the time when the ambient temperature will be as specified. Some circuits probably do not carry their full load during the hottest part of the day or when the sun is at its brightest, so that an ambient temperature of 40 °C for outdoor cables is probably reasonably safe for certain selected circuits; otherwise, use 50 °C. Refer to the NEC® Article 310 ampacity tables and associated notes for the calculations to be used for outdoor installations and Article 392 for cables installed in cable tray.

c) *Underground.* The ambient temperature used for underground cables varies in different sections of the country. For the northern sections, an ambient temperature of 20 °C is commonly used. For the central part of the country, 25 °C is commonly used, while for the extreme south and southwest, an ambient of 30 °C may be necessary. The exact geological boundaries for these ambient temperatures cannot be defined, and the maximum ambient should be measured in the earth at a point away from any sources of heat at the depth at which the cable will be buried. Changes in the earth ambient temperature will lag changes in the air ambient temperature by several weeks.

The thermal characteristics of the medium surrounding the cable are of primary importance in determining the current-carrying capacity of the cable. The type of soil in which the cable or duct bank is buried has a major effect on the current-carrying capacity of cables. Porous soils, such as gravel and cinder fill, usually result in a temperature increase and lower ampacities than normal sandy or clay soil. The type of soil and its thermal resistivity should be known before the size of the conductor is calculated.

The moisture content of the soil has a major effect on the current-carrying capacity of cables. In dry sections of the country, cables may have to be de-rated or other precautions taken to compensate for the increase in thermal resistance due to the lack of moisture. On the other hand, in ground which is continuously wet or under tidewater conditions, cables may carry higher than normal currents. Shielding for even 2400 V circuits is necessary for continuously wet or alternately wet and dry conditions. Where the cable passes from a dry area to a wet area, which provides natural shielding, there will be an abrupt voltage gradient stress, just as at the end of shielded cables terminated without a stress cone. Non-shielded cables specifically designed for this service are available. Alternate wet and dry conditions have also been found to accelerate the progress of water treeing in solid dielectric insulations.

Ampacities in the NEC® tables take into account the grouping of adjacent circuits. For ambient temperatures different from those specified in the tables, more than three conductors in a cable or raceway, or other installation conditions, the de-rating factors to be applied for low-voltage cables are contained in Table 310.15(B)(2)(a), and Table 310.16 through Table 310.20. De-rating factors for cables rated 2001 V through 35 000 V used for conditions where the ambient is different from that specified in Table 310.60(C)(67) through Table 310.60(C)(86) are calculated per Table 310.60(C)(4) or the equation provided in 310.60(C)(4).

9.3.3 Emergency overload criteria

The normal loading limits of insulated wire and cable are based on many years of practical experience and represent a rate of deterioration that results in the most economical and useful life of such cable systems. The rate of deterioration is expected to result in a useful life of 20 years to 30 years. The life of cable insulation is about halved, and the average rate of thermally caused service failures about doubled for each 5 °C to 15 °C increase in normal daily load temperature. Additionally, sustained operation over and above maximum rated operating temperatures or ampacities is not a very effective or economical expedient because the temperature rise is directly proportional to the conductor loss, which increases as the square of the current. The greater voltage drop might also increase the risks to equipment and service continuity.

As a practical guide, the Insulated Cable Engineers Association (ICEA) has established maximum emergency overload temperatures for various insulations. Operation at these emergency overload temperatures should not exceed 100 hours/year, and such 100 hour overload periods should not exceed five during the life of the cable. Table 26 provides uprating factors for short-time overloads for various types of insulated cables. The uprating factor, when multiplied by the nominal current rating for the cable in a particular installation, will give the emergency or overload current rating for the particular insulation.

A more detailed discussion on emergency overload and cable protection is contained in IEEE Std 242™-2001 (*IEEE Buff Book™*), Chapter 9.

Table 26 —Operating for short time overloads (1)

Insulation type	Voltage class (kV)	Conductor operating temperature (°C)	Conductor overload temperature (°C)	Uprating factors for ambient temperature							
				20 °C		30 °C		40 °C		50 °C	
				Cu	Al	Cu	Al	Cu	Al	Cu	Al
Paper (solid type)	9	95	115	1.09	1.09	1.11	1.11	1.13	1.13	1.17	1.17
	29	90	110	1.10	1.10	1.12	1.12	1.15	1.15	1.19	1.19
	49	80	100	1.12	1.12	1.15	1.15	1.19	1.19	1.25	1.25
	69	65	80	1.13	1.13	1.17	1.17	1.23	1.23	1.38	1.38
Varnished cambric	5	85	100	1.09	1.08	1.10	1.10	1.13	1.13	1.17	1.17
	15	77	85	1.05	1.05	1.07	1.07	1.09	1.09	1.13	1.13
	28	70	72								
Polyethylene (natural)	35	75	95	1.13	1.13	1.17	1.17	1.22	1.22	1.30	1.30
SBR rubber	0.6	75	95	1.13	1.13	1.17	1.17	1.22	1.22	1.30	1.30
	5	90	105	1.08	1.08	1.09	1.09	1.11	1.11	1.14	1.14
Butyl RHH	15	85	100	1.09	1.08	1.10	1.10	1.13	1.13	1.17	1.17
	35	80	95	1.09	1.09	1.11	1.11	1.14	1.14	1.20	1.20
Oil-base rubber	35	70	85	1.11	1.11	1.14	1.14	1.20	1.20	1.29	1.29
Polyethylene (cross-linked)	35	90	130	1.18	1.18	1.22	1.22	1.26	1.26	1.33	1.33
Silicone rubber	5	125	150	1.08	1.08	1.09	1.09	1.10	1.10	1.12	1.11
EPR rubber	35	90	130	1.18	1.18	1.22	1.22	1.26	1.26	1.33	1.33
Chlorosulfonated polyethylene (see Note 2)	0.6	75	95	1.13	1.13	1.17	1.17	1.22	1.22	1.30	1.30
Polyvinyl chloride	0.6	60	85	1.22	1.22	1.30	1.30	1.44	1.44	1.80	1.79
	0.6	75	95	1.13	1.13	1.17	1.17	1.22	1.22	1.30	1.30

NOTE 1—To be applied to normal rating determined for such installation conditions
NOTE 2—For example, Hypalon®

9.3.4 Voltage drop criteria

The supply conductor, if not of sufficient size, will cause excessive voltage drop in the circuit, and the drop will be in direct proportion to the circuit length. Proper starting and running of motors, lighting equipment, and other loads that have heavy in-rush currents must be considered. The NEC® recommends that the steady-state voltage drop in either feeders or branch circuits be no more than 3%, and the total drop of feeders plus branch circuits be no more than 5% overall.

9.3.5 Fault current criteria

Under short-circuit conditions, the temperature of the conductor rises rapidly. Then, depending upon the thermal characteristics of the insulation, sheath, surrounding materials, etc., the conductor cools off slowly after the short-circuit condition is removed. For each insulation, the ICEA recommends a transient temperature limit for short-circuit duration times not in excess of 10 s.

Failure to check the conductor size for short-circuit heating could result in permanent damage to the cable insulation due to disintegration of the insulation material, which may be accompanied by smoke and generation of combustible vapors. These vapors will, if sufficiently heated, ignite, possibly starting a fire. Less seriously, the insulation or sheath of the cable may be expanded to produce voids leading to subsequent failure. This becomes especially important in cables rated 5 kV and higher.

In addition to the thermal stresses, mechanical stresses are set up in the cable through expansion when heated. As the heating is usually very rapid, these stresses may result in undesirable cable movement. However, on modern cables, reinforcing binders and sheaths considerably reduce the effect of such stresses. Within the range of temperatures expected with coordinated selection and application, the mechanical aspects can normally be discounted except with very old or lead-sheathed cables.

During short-circuit or heavy pulsing currents, single-conductor cables will be subjected to forces that tend to either attract or repel the individual conductors with respect to each other. Therefore, cables installed in cable trays, racks, switchgear, motor control centers, or switchboard cable compartments, should be secured to prevent damage caused by such movements.

The minimum conductor size requirements for various rms short-circuit currents and clearing times are shown in Table 27. The initial and final conductor temperatures from ICEA P-32-382 (2007) are shown for the various insulations. Table 24 provides conductor temperatures (maximum operating, maximum overload, and maximum short-circuit current) for various insulated cables.

The shield can be damaged if exposed to excessive fault currents. ICEA P-45-482 (2007) recommends that the ground-fault current not exceed 2000 A for 1/2 s. Some lighter duty shield constructions may have a lower current limit; check with the cable manufacturer. To limit ground-fault shield conductor exposure, the recommended practice is to utilize current-limiting overcurrent protective devices or employ low-resistance grounded supply systems for a maximum ground-fault current of 400 A to 2000 A with suitably sensitive relaying. Without such limiting, it is likely that the occurrence of a ground fault could require replacement of substantial lengths of cable. Grounding of the shield at all splice and termination points will direct fault currents into multiple paths and reduce shield damage. A more detailed discussion of fault current and cable protection is contained in IEEE Std 242™-2001 (*IEEE Buff Book™*).

Table 27 —Minimum conductor sizes, in AWG or kcmil,
for indicated fault current and clearing times

Total rms current (amperes)	Polyethylene and polyvinyl chloride, 75 °C to 150 °C				Oil base and SBR, 75 °C to 200 °C				Cross-linked polyethylene and EPR, 90 °C to 250 °C			
	1/2 cycle (0.0083 s)		10 cycles (0.166 s)		1/2 cycle (0.0083 s)		10 cycles (0.166 s)		1/2 cycle (0.0083 s)		10 cycles (0.166 s)	
	Cu	Al	Cu	Al	Cu	Al	Cu	Al	Cu	Al	Cu	Al
5000	10	8	4	2	10	8	4	3	12	10	4	3
15 000	6	4	2/0	4/0	6	4	1/0	3/0	6	4	1	3/0
25 000	3	2	4/0	350	4	2	3/0	250	4	3	3/0	250
50 000	1/0	2/0	400	700	1	2/0	350	500	2	1/0	300	500
75 000	2/0	4/0	600	1000	1/0	3/0	500	750	1/0	3/0	500	700
100 000	4/0	300	800	1250	3/0	250	700	1000	2/0	4/0	600	1000

9.3.6 Frequency criteria

In general, three-phase, 400 Hz power systems are designed in the same way as 60 Hz systems; however, the specifier must be aware that the higher frequency will increase the skin and proximity effects on the conductors, thereby increasing the effective copper resistance. For a given current, this increase in resistance results in increased heating and may require a larger conductor. The higher frequency will also increase the reactance, and this, combined with the increased resistance, will increase the voltage drop. The higher frequency will also increase the effect of magnetic materials upon cable reactance and heating. For this reason, the cables should not be installed in steel or magnetic conduit, steel wireway, or run along magnetic structural members within the building.

The curves in Figure 31 show the ac/dc resistance ratio that exists on a 400 Hz system and the resulting reduction in current rating that is necessary from a heating standpoint to counteract the effect of the increased frequency.

The reactance can be taken as directly proportional to the frequency without introducing any appreciable errors. This method of determining reactance does not take into account the reduction due to proximity effect, but this change is not large and the error introduced by neglecting it is small.
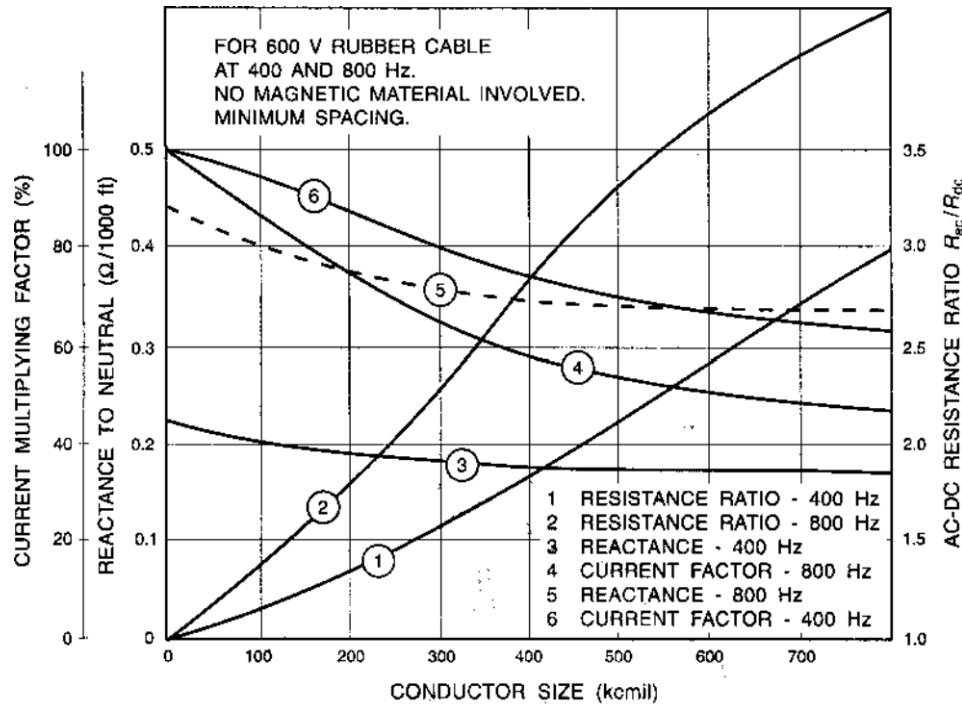

Figure 31 —AC/DC resistance ratio on a 400 Hz system

The curves are applicable to any 600 V cable in the same nonmagnetic conduit, or to any Type MC cable with an aluminum or bronze sheath or interlocking armor.

When voltage drop is the limiting factor, then paralleling smaller conductors should be considered.

9.3.7 Elevated ambient temperature

The ambient temperature of the area where cables are installed must be considered in determining the allowable ampacity of the circuit.

Cables and insulated conductors rated 2000 V or less, installed in areas where the ambient temperature is higher than that permitted in NEC® Table 310-16 through Table 310-19, must have the allowable ampacity reduced by the ampacity correction factors listed in appropriate table.

The ampacity of cables and insulated conductors rated over 2000 V, installed in areas where the ambient temperature is either higher or lower than the temperatures specified in NEC® Table 310-69 through Table 310-84, may be determined by using the formula contained in NEC® 310.60(C)(4).

9.3.8 Hot-spot temperature criteria

The allowable ampacity of a cable or insulated conductor must be reduced whenever more than 6 ft of the run is in a higher ambient temperature area. Refer to 9.3.7 for the applicable correction factors.

9.3.9 Termination criteria

Equipment termination requirements must be considered; e.g., the manufacturer of a circuit breaker may specify a minimum conductor size for a particular breaker rating. Also, on 600 V terminations, the rating of the termination may require the cable to be operated at a lower temperature, 60 °C or 75 °C.

9.4 Installation

There are a variety of ways to install power distribution cables in industrial facilities. The engineer's responsibility is to select the method most suitable for each particular application. Each method has characteristics that make it more suitable for certain conditions than others; that is, each method will transmit power with a unique combination of reliability, safety, economy, and quality for a specific set of conditions. These conditions include the quantity and characteristics of the power being transmitted, the distance of transmission, and the degree of exposure to adverse mechanical and environmental conditions.

9.4.1 Layout

The first consideration in wiring systems layout is to keep the distance between the source and the load as short as possible. This consideration should be tempered by many other important factors to arrive at the lowest cost system that will operate within the reliability, safety, economy, and performance required. Some other factors that must be considered for various routings are the cost of additional cable and raceway versus the cost of additional supports; inherent mechanical protection provided in one alternative versus additional protection required in another; clearance for and from other facilities; and the need for future revision.

9.4.2 Open wire

This method was used extensively in the past. Although it has now been replaced in most applications, it is still quite often used for primary power distribution over large areas where conditions are suitable.

Open wire construction consists of single conductors on insulators that are mounted on poles or structures. The conductors may be bare or have a covering or jacket for protection against corrosion or abrasion.

The attractive features of this method are its low initial cost and the fact that damage can generally be detected and repaired quickly. On the other hand, the non-insulated conductors are a safety hazard and are also very susceptible to mechanical damage and electrical outage from birds, animals, lightning, etc. There is an increased safety hazard where crane or boom truck use may be involved. In some areas, insulator contamination or conductor corrosion can result in increased maintenance costs.

Due to the large conductor spacing, open wire circuits have a higher reactance than circuits with more closely spaced conductors, producing a larger voltage drop. This problem is reduced by operating at a higher voltage and higher power factor.

Exposed open wire circuits are more susceptible to outages from lightning than other installation methods. The problem may be minimized through the use of overhead ground wires, surge arresters, or special insulators.

9.4.3 Aerial cable

Aerial cable is usually used for incoming or service distribution between commercial buildings. As a logical replacement for open wiring, it provides safety and reliability and requires less space. Properly protected cables are generally not a safety hazard and are not easily damaged by casual contact. They are, however, open to the same objections as open wire in regard to vertical and horizontal clearances. Aerial cables are frequently used in place of the more expensive conduit systems, where the mechanical protection of the conduit is not required. They are also generally more economical for long runs of one or two cables than are cable tray installations. It is cautioned that aerial cable having a portion of the run in conduit must be de-rated to the ampacity in conduit for this condition.

Aerial cables may be either self-supporting or messenger-supported. They may be attached to pole lines or structures. Self-supporting aerial cables have high tensile strength conductors for this application.

Multiple single conductors, Types MV, THW, RHH or RHW, both without outer braids; or multi-conductor cables, Types MI, MC, SE, UF, TC, MV, or other factory-assembled multi-conductor control, signal, or power cables that are identified for the use in NEC®, Article 321, may be messenger-supported.

Cables may be messenger-supported either by spirally wrapping a steel band around the cables and the messenger or by pulling the cable into rings suspended from the messenger. The spiral wrap method is used for factory-assembled cable, while both methods are used for field assembly. A variety of spinning heads are available for application of the spiral wire banding in the field. The messenger used on factory-assembled messenger-supported wiring is required to be copper-covered steel or a combination of copper-covered steel and copper, and the assembly must be secured to the messenger by a flat copper binding strip. Single insulated conductors should be cabled together.

Factory-preassembled aerial cables are particularly susceptible to installation damage from high stress at support sheaves while being pulled in.

Self-supporting cable is suitable for only relatively short spans. Messenger-supported cable can span longer distances, depending on the weight of the cable and the tensile strength of the messenger. The supporting messenger provides strength to help withstand climatic rigors or mechanical shock. The messenger must be grounded in accordance with the NEC®.

A convenient feature available in one form of factory assembled aerial cable makes it possible to form a slack loop to connect a circuit tap without cutting the cable conductors. This is done by reversing the direction of spiral of the conductor cabling every 10 ft to 20 ft.

Spacer cable is an electric distribution line construction that consists of an assembly of one or more covered conductors separated from each other and supported from a messenger by insulating spacers. This is another economical means of transmitting power overhead between buildings. Available for use in three-phase 5 kV to 15 kV grounded or ungrounded systems, the insulated non-shielded phase conductors provide protection from accidental discharge through contact with ground level equipment, such as aerial ladders or crane booms. Uniform-line electrical characteristics are obtained through the balanced geometric positioning of the conductors with respect to each other by the use of plastic or ceramic spacers located at regular intervals along the line. Low terminating costs are obtained because the conductors are non-shielded.

9.4.4 Open runs

This is a low-cost method where adequate support surfaces are available between the source and the load. It is most useful in combination with other methods, such as branch runs from cable trays, and when adding new circuits to existing installations.

This method employs multi-conductor cable attached to surfaces, such as structural beams and columns. Type MC cable is permitted to be installed in this manner in industrial facilities as well as power-limited control and telephone circuits. For architectural reasons in office buildings, it is usually limited to service areas, above hung ceilings, and electric shafts.

9.4.5 Cable tray

A cable tray is defined in the NEC® as "a unit or assembly of units or sections, and associated fittings, forming a rigid structural system used to support cables and raceways." These supports include ladders, troughs, and channels, and have become very popular in industrial electric systems for the following reasons: low installation cost, system flexibility, improved reliability, accessibility for repair or addition of cables, and space saving when compared with conduit where a larger number of circuits with common routing are involved.

Cable trays are available in a number of styles, materials, and mechanical load-carrying capabilities. Special coatings or materials for corrosion protection are available.

Initial planning of a cable tray should consider occupancy requirements as given in the NEC® and also allow additional space for future system expansion.

Covers, either ventilated or nonventilated, may be used when additional mechanical protection is required or for additional electrical shielding when communication circuits are involved. Where cable trays are continuously covered for more than 6 ft with solid, unventilated covers, the cable ampacity rating must be de-rated as required by the NEC®, Section 392.

A solid fixed barrier is required for separation of cables rated over 600 V from those rated 600 V or less. Barrier strips are not required when the cables over 600 V are Type MC.

Seals or fire stops may be required when passing through walls, partitions, or elsewhere to minimize flame propagation.

In stacked tray installations, it is good practice to separate voltages, locating the lowest voltage cables in the bottom tray and increasingly higher voltage cables in ascending order of trays. In a multiphase system, all phase conductors should be installed closely grouped in the same tray.

A cable tray provides a convenient economical support method when more than three cables are being routed in the same direction. Single conductors of size 1/0 AWG and larger that are identified for the use are permitted in cable tray in industrial establishments. Type MC cable can be installed in cable tray and, when only one or two cables have to be routed to a separate location, the cable can then be installed as open runs of cable. Type TC cable, as well as single conductors, requires the use of a raceway between the cable tray and the termination point.

The steel or aluminum metal in a cable tray can also be used as an equipment grounding conductor when the tray sections are listed by a nationally recognized testing laboratory as having adequate cross-sectional area and are bonded using mechanical connectors or bonding jumpers. Refer to the NEC®, Section 392.7, for complete requirements.

9.4.6 Cable bus

Cable bus is used for transmitting large amounts of power over relatively short distances. It is a more economical replacement of conduit or busway systems, but more expensive than cable tray. Cable bus is also more reliable, generally safer, and requires less maintenance than open wire or bus systems.

Cable bus is a hybrid between cable tray and busway. It uses insulated conductors in an enclosure that is similar to cable tray with covers. The conductors are supported at maintained spacings by nonmetallic spacer blocks. Cable buses are furnished either as components for field assembly or as completely assembled sections. The use of completely assembled sections is recommended when the run is short enough that splices may be avoided. Multiple sections requiring joining may preferably employ the continuous conductors.

The conductors are generally spaced one cable diameter apart so that the rating in air may be attained. This spacing is also close enough to provide low reactance, resulting in minimum voltage drop.

9.4.7 Conduit

Among conduit systems, rigid steel provides a greater degree of mechanical protection available in above-ground conduit systems. Unfortunately, this is also a relatively high cost system. For this reason, it is being replaced, where possible, by other types of conduit and wiring systems. Where applicable, rigid aluminum, rigid nonmetallic conduit (NMC), electrical metallic tubing (EMT), intermediate metal conduit (IMC), electrical nonmetallic tubing (ENMT), and plastic, fiberglass, and cement ducts may be used. Cable trays and open runs of Type MC cable are also being utilized.

Conduit systems offer some degree of flexibility in permitting replacement of existing conductors with new ones. However, in case of fire or short-circuit current faults, it may be impossible to remove the conductors. In this case, it is necessary to replace both conduit and wire at great cost and delay. Also, during fires, conduits may transmit corrosive fumes into equipment where these gases can do a lot of damage. To keep flammable gases out of such areas, seals must be installed.

With magnetic conduits, an equal number of conductors of each phase must be installed in each conduit; otherwise, losses and heating will be excessive. For example, a single conductor should not be installed in steel conduit.

Refer to the NEC® for regulations on conduit use.

Underground ducts are used where it is necessary to provide good mechanical protection (e.g., when overhead conduits are subject to extreme mechanical abuse or when the cost of going underground is less than providing overhead supports). In the latter case, direct burial (without conduit) may be satisfactory under certain circumstances.

Underground ducts use rigid steel, plastic, or fiberglass conduits encased in concrete, or precast with multihole concrete duct banks with close-fitting joints. When the added mechanical protection of concrete is not required, heavy wall versions of fiberglass conduits are direct buried as are rigid steel and plastic conduits. Medium-voltage, low-voltage, signal and communications systems should not be installed in the same manhole. Manholes intended for cable splices or for drain provisions on long length cables should have adequate provisions for grounding.

Cables used in underground conduits must be suitable for use in wet areas. Some cost savings can be realized by using flexible plastic conduits with factory installed conductors.

Where a relatively long distance between the point-of-service entrance into a building and the service entrance protective device is unavoidable, the requirements of the NEC®, Section 230.6, apply. The

conductors must be placed under at least 2 in of concrete beneath the building; or they must be placed in conduit or duct and enclosed by concrete or brick not less than 2 in thick. They are then considered outside the building.

9.4.8 Direct burial

Cables may be buried directly in the ground where permitted by the NEC® when the need for future maintenance along the cable run is not anticipated nor the protection of conduit required. The cables used must be suitable for this purpose; that is, they must be resistant to moisture, crushing, soil contaminants, and insect and rodent damage. Direct buried cables rated over 600 V must be shielded and provide an exterior ground path for personnel safety in the event of accidental dig-in. Multi-conductor non-shielded Type MC cables rated up to 5000 V are also permitted to be direct buried. Refer to the NEC®, Table 300.50, for minimum depth requirements.

The cost savings of this method over duct banks can vary from very little to a considerable amount. Cable trenching or burying machines, when appropriate, can significantly reduce the installation cost of direct buried cable, particularly in open field construction, such as in industrial parks. While this system cannot readily be added to or maintained, the current-carrying capacity of a cable of a given size is usually greater than that for cables in ducts. Buried cable must have selected backfill for suitable heat dissipation. It should be used only when the chances of its being disturbed are minimal or it should be suitably protected. Relatively recent advances in the design and operating characteristics of cable fault location equipment and subsequent repair methods and material have diminished the maintenance mean time to repair.

9.4.9 Hazardous (classified) locations

Wire and cable installed in locations where fire or explosion hazards may exist must comply with the NEC®, Article 500 through Article 517. The authorized wiring methods are dependent upon the class and division of the specific area (see Table 28). The wiring method must be approved for the class and division but is not dependent upon the group, which defines the hazardous substance.

Equipment and the associated wiring system approved as intrinsically safe is permitted in any hazardous location for which it has been approved. However, the installation must prevent the passage of gases or vapors from one area to another. Intrinsically safe equipment and wiring is intended to prevent the release of sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of a specific flammable or combustible atmospheric mixture in its most easily ignitable concentration.

Seals must be provided in the wiring system to help prevent the passage of the hazardous atmosphere along the wiring system from one division to another or from a Division I or Division II hazardous location to a non-hazardous location. The sealing requirements are defined in the NEC®, Article 501 through Article 503. The use of multi-conductor cables with a gas/vaportight continuous outer sheath, either metallic or nonmetallic, can significantly reduce the sealing requirements in Class I, Division 2 hazardous locations.

9.4.10 Installation procedures

Care must be taken in the installation of raceways to ensure that no sharp edges exist to cut or abrade the cable as it is pulled in. Another important consideration is to not exceed the maximum allowable tensile strength or the manufacturer's recommendation for the maximum sidewall pressure of a cable. These forces are directly related to the force exerted on the cable while it is being pulled in. The forces can be decreased by shortening the length of each pull and reducing the number of bends. The force required for pulling a given length can be reduced by the application of a pulling compound on cables in conduit and the use of rollers in cable trays.

Table 28 —Wiring methods for hazardous locations

Wiring method	Class I Division		Class II Division		Class III Division
	1	2	1	2	1 or 2
Threaded rigid metal conduit	X	X	X	X	X
Threaded steel intermediate metal conduit	X	X	X	X	X
Rigid metal conduit				X	X
Intermediate metal conduit				X	X
Electrical metallic tubing				X	X
Rigid nonmetallic conduit					X
Type MI mineral insulated cable	X	X	X	X	X
Type MC metal-clad cable		X		X	X
Type SNM shielded nonmetallic cable		X		X	X
Type MV medium-voltage cable		X			
Type TC power and control tray cable		X			
Type PLTC power-limited tray cable		X			
Enclosed gasketed busways or wireways		X			
Dust-tight wireways				X	X

Source: Based on the NEC®.

When the cable is to be pulled by the conductors, the maximum tension in pounds is limited to 0.008 times the area of the conductors, in circular mils, within the construction. The allowable tension should be reduced by 20% to 40% when several conductors are being pulled simultaneously since the tension is not always evenly distributed among the conductors. This allowable tension must be further reduced when the cable is pulled by a grip placed over the outer covering. A reasonable figure for most jacketed constructions would be 1000 lb per grip; but the calculated conductor tension should not be exceeded. Pulling eyes connected to each conductor provide the maximum allowable pulling tension. Reusable pulling eyes are available.

Sidewall pressures on most single conductors limit pulling tensions to approximately 450 lbs times the cable diameter (inches) times the radius of the bend (feet). Triplexed and paralleled cables would use their single conductor diameters and a factor of 225 lbs and 675 lbs, respectively, instead of the 450 lb factor for a single conductor.

For duct installations involving many bends, it is preferable to feed the cable into the end closest to the majority of the bends (since the friction through the longer duct portion without the bends is not yet a factor) and pull from the other end. Each bend gives a multiplying factor to the tension it sees; therefore, the shorter runs to the bends will keep this increase in pulling tensions to a minimum. However, it is best to calculate pulling tensions for installation from both ends of the run and install from the end requiring the least tension.

The minimum bending radii is 8 times the overall cable diameter for non-shielded single and multi-conductor cables and 12 times for metal tape shielded or lead covered cables. The minimum bending radius for non-shielded Type MC cable with interlocking armor or a corrugated sheath is 7 times the overall diameter of the metallic sheath; for shielded cables, the minimum bending radius is 12 times the overall diameter of one of the individual conductors or 7 times the overall diameter of the multi-conductor cable, whichever is greater. Type MC cable with a smooth metallic sheath requires a greater minimum bending radius; refer to the NEC®, Section 330.24. The minimum bending radius is applicable to bends of even a fraction of an inch in length, not just the average of a long length being bent.

When installing cables in wet underground locations, the cable ends must be sealed to prevent entry of moisture into the conductor strands. These seals should be left intact or remade after pulling if disrupted, until splicing, terminating, or testing is to be done. This practice is recommended to avoid unnecessary corrosion of the conductors and to safeguard against entry of moisture into the conductor strands, which would generate steam under overload, emergency loadings, or short-circuit conditions after the cable is energized.

9.5 Connectors

9.5.1 Types available

Connectors are classified as thermal or pressure, depending upon the method used to attach them to the conductor.

Thermal connectors use heat to make soldered, silver soldered, brazed, welded, or cast-on terminals. Soldered connections have been used with copper conductors for many years, and their use is well understood. Aluminum connections may also be soldered satisfactorily with the proper materials and technique. However, soldered joints are not commonly used with aluminum. Shielded arc welding of aluminum terminals to aluminum cable makes a satisfactory termination for cable sizes larger than 4/0 AWG. Torch brazing and silver soldering of copper cable connections are in use, particularly for underground connections with bare conductors such as in grounding mats. Exothermic welding kits utilizing carbon molds are also used for making connections with bare copper or bimetallic (copperweld) cable for ground mats and for junctions that will be below grade. These are satisfactory as long as the conductors to be joined are dry and the welding charge and tool are proper. The exothermic welding process has also proved satisfactory for attaching connectors to insulated power cables.

Mechanical and compression pressure connectors are used for making joints in electric conductors. Mechanical connectors obtain the pressure to attach the connector to the electric conductor from an integral screw, cone, or other mechanical parts. A mechanical connector thus applies force and distributes it suitably through the use of bolts or screws and properly designed sections. The bolt diameter and number of bolts are selected to produce the clamping and contact pressures required for the most satisfactory design. The sections are made heavy enough to carry rated current and withstand the mechanical operating conditions. These are frequently not satisfactory with aluminum, since only a portion of the strands is distorted by this connector.

Compression connectors are those in which the pressure to attach the connector to the electric conductor is applied externally, changing the size and shape of the connector and conductor.

The compression connector is basically a tube with the inside diameter slightly larger than the outer diameter of the conductor. The wall thickness of the tube is designed to carry the current, withstand the installation stresses, and withstand the mechanical stresses resulting from thermal expansion of the conductor. A joint is made by compressing the conductor and tube into another shape by means of a specially designed die and tool. The final shape may be indented, cup, hexagon, circular, or oval. All methods have in common the reduction in cross-sectional area by an amount sufficient to assure intimate and lasting contact between the connector and the conductor. Small connectors can be applied with a small hand tool. Larger connectors are applied with a hydraulic compression tool.

A properly crimped joint deforms the conductor strands sufficiently to have good electrical conductivity and mechanical strength, but not so much that the crimping action overcompresses the strands, thus weakening the joint.

Mechanical and compression connectors are available as tap connectors. Many connectors have an independent insulating cover. After a connection is made, the cover is assembled over the joint to insulate and, in some cases, to seal against the environment.

9.5.2 Connectors for aluminum

Aluminum conductors are different from copper in several ways, and these property differences should be considered in specifying and using connectors for aluminum conductors (see Table 22). The normal oxide coating on aluminum has a relatively high electrical resistance. Aluminum has a coefficient of thermal

expansion greater than copper. The ultimate and the yield strength properties and the resistance to creep of aluminum are different from the corresponding properties of copper. Corrosion is possible under some conditions because aluminum is anodic to other commonly used metals, including copper, when electrolytes even from humid air are present.

a) *Mechanical properties and resistance to creep.* Creep is commonly referred to as the continued deformation of the material under stress. The effect of excessive creep resulting from the use of an inadequate connector that applies excessive stress could be the relaxation of contact pressure within the connector, and a resulting deterioration and failure of the electric connection. In mechanical connectors for aluminum, as for copper, proper design can limit residual unit bearing loads to reasonable values with a resulting minimum plastic deformation and creep subsequent to that initially experienced on installation. Connectors for aluminum wire can accommodate a range of conductor sizes, provided that the design takes into account the residual pressure on both minimum and maximum conductors.

b) *Oxide film.* The surface oxide film on aluminum, though very thin and quite brittle, has a high electrical resistance and, therefore, must be removed or penetrated to ensure a satisfactory electric joint. This film can be removed by abrading with a wire brush, steel wool, emery cloth, or similar abrasive tool or material. A plated surface, whether on the connector or bus, should never be abraded; it can be cleaned with a solvent or other means that will not remove the plating.

Some aluminum fittings are factory-filled with a connection aid compound, usually containing particles that aid in obtaining low contact resistance. These compounds act to seal connections against oxidation and corrosion by preventing air and moisture from reaching contact surfaces. Connection to the inner strands of a conductor requires deformation of these strands in the presence of the sealing compound to prevent the formation of an oxide film.

c) *Thermal expansion.* The linear coefficient of thermal expansion of aluminum is greater than that of copper and is important in the design of connectors for aluminum conductors. Unless provided for in the design of the connector, the use of metals with coefficients of expansion less than that of aluminum can result in high stresses in the aluminum during heat cycles, causing additional plastic deformation and significant creep. Stresses can be significant, not only because of the differences of coefficients of expansion, but also because the connector may operate at an appreciably lower temperature than the conductor. This condition will be aggravated by the use of bolts that are of a dissimilar metal or have different thermal expansion characteristics from those of the terminal.

d) *Corrosion.* Direct corrosion from chemical agents affects aluminum no more severely, and in most cases less, than it does copper. However, since aluminum is more anodic than other common conductor metals, the opportunity exists for galvanic corrosion in the presence of moisture and a more cathodic metal. For this to occur, a wetted path must exist between external surfaces of the two metals in contact to set up an electric cell through the electrolyte (moisture), which results in erosion of the more anodic of the two, in this instance, the aluminum.

Galvanic corrosion can be minimized by the proper use of a joint compound to keep moisture away from the points of contact between dissimilar metals. The use of relatively large aluminum anodic areas and masses minimizes the effects of galvanic corrosion. Plated aluminum connectors must be protected by taping or other sealing means.

e) *Types of connectors for aluminum conductors.* UL has listed connectors approved for use on aluminum that have successfully withstood UL performance tests as specified by UL 486b-2011. Both mechanical and compression connectors are available. The most satisfactory connectors are specifically designed for aluminum conductors to prevent any possible troubles from creep, the presence of oxide film, and the differences of coefficients of expansion between aluminum and other metals. These connectors are usually satisfactory for use on copper conductors in noncorrosive locations. The connection of an aluminum connector to a copper or aluminum pad is similar to the connection of bus bars. When both the pad and the connector are plated and the connection is made indoors, few precautions are necessary. The contact surfaces should be clean; if not, a solvent should be used. Abrasive cleaners are undesirable since the plating may be removed. In normal application, steel, aluminum, or copper alloy bolts, nuts, and flat washers may be used. A light film of a joint compound is acceptable, but not mandatory. When either of the contact surfaces

is not plated, the bare surface should be cleaned by wire brushing, then coated with a joint compound. Belleville washers are suggested for heavy duty applications where cold flow or creep may occur, or where bare contact surfaces are involved. Flat washers should be used wherever Belleville washers or other load concentrating elements are employed. The flat washer must be located between the aluminum lug, pad, or bolt and the outside edge of the Belleville washer with the neck or crown of the Belleville against the bolting nut to obtain satisfactory operation. In outdoor or corrosive atmosphere, the above applies with the additional requirement that the joint be protected. An unplated aluminum-to-aluminum connection can be protected by the liberal use of a nonoxide compound.

In an aluminum-to-copper connection, a large aluminum volume compared to the copper is important as well as the placement of the aluminum above the copper. Again, coating with a joint compound is the minimum protection; painting with a zinc chromate primer or thoroughly sealing with a mastic or tape is even more desirable. Plated aluminum should be completely sealed against the elements.

f)   *Welded aluminum terminals.* For aluminum cables 250 kcmil and larger which carry large currents, excellent terminations can be made by welding special terminals to the cable. This is best done by the inert gas shielded metal arc method. The use of inert gas eliminates the need for any flux to be used in making the weld. The welded terminal is shorter than a compression terminal because the barrel for holding the cable can be very short. It has the advantage of requiring less room in junction or equipment terminal boxes. Another advantage is the reduced resistance of the connection. Each strand of the cable is bonded to the terminal, resulting in a continuous metal path for the current from every strand of the cable to the terminal.

Welding of these terminals to the conductors may also be done by using the tungsten electrode type of ac welding equipment. The tungsten arc method is slower but, for small work, gives somewhat better control.

The tongues or pads of the welded terminals, such as the large compression connectors, are available with bolt holes to conform to NEMA FB 11-2000 for terminals to be used on equipment.

g)   *Procedure for Connecting Aluminum Conductors* (Figure 32)

1)   When cutting cable, avoid nicking the strands. Nicking makes the cable subject to easy breakage [see Figure 32(a)].
2)   Contact surfaces should be cleaned. The abrasion of contact surfaces is helpful even with new surfaces and is essential with weathered surfaces. Do not abrade plated surfaces [see Figure 32(b)].
3)   Apply joint compound to the conductor if the connector does not already have it [see Figure 32(c)].
4)   Use only connectors specifically tested and approved for use on aluminum conductors.
5)   On mechanical connectors, tighten the connector with a screwdriver or wrench to the required torque. Remove excess compound [see Figure 32(d)].
6)   On compression connectors, crimp the connector using proper tool and die. Remove excess compound [see Figure 32(e)].
7)   Always use a joint compound compatible with the insulation and as recommended by the manufacturer. The oxide film penetrating or removing properties of some compounds aids in obtaining good initial conductivity. The corrosion inhibiting and sealing properties of some compounds help ensure the maintenance of continued good conductivity and prevention of corrosion.
8)   When making an aluminum-to-copper connection that is exposed to moisture, place the aluminum conductor above the copper. This prevents soluble copper salts from reaching the aluminum conductor, which could result in corrosion. If there is no exposure to moisture, the relative position of the two metals is not important.

9) When using insulated conductors outdoors, extend the conductor insulation or covering as close to the connector as possible to minimize weathering of the joint. Outdoors, whenever possible, joints should be completely protected by tape or other means. When outdoor joints are covered or protected, the protection should completely exclude moisture, as the retention of moisture could lead to severe corrosion.
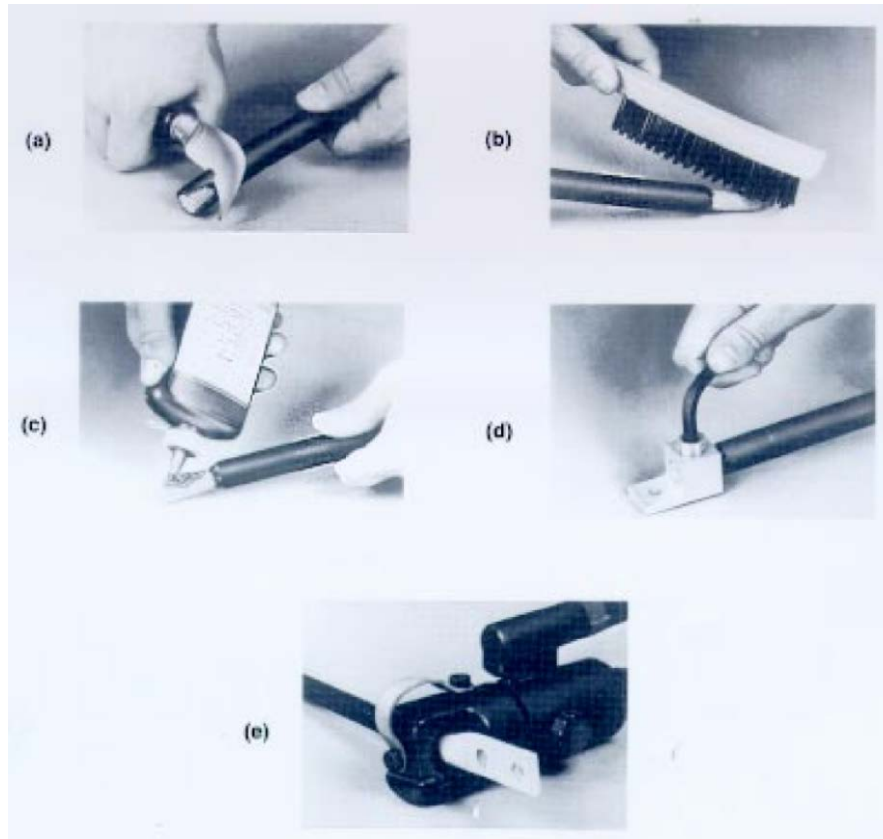

Figure 32 —Procedures for connecting aluminum conductors

9.5.3 Connectors for cables of various voltage

Standard mechanical or compression connectors are recommended for all primary voltages provided the bus is non-insulated. Welded connectors may also be used for conductors sized in circular mils. Up to 600 V, standard connector designs present no problem for insulated or non-insulated conductors. The standard compression connectors are suitable for use on non-shielded conductors up to 5 kV. Above 5 kV and on shielded 5 kV conductors, stress considerations make it desirable to use tapered end compression connectors or semiconducting tape construction to provide the same effect.

9.5.4 Performance requirements

Electric connectors for industrial plants are designed to meet the requirements of the NEC®. They are evaluated on the basis of their ability to pass secureness, heating, heat cycling, and pull-out tests as specified in UL 486a-486b-2011. These standards were revised to incorporate more stringent requirements for aluminum terminating devices. The reader is cautioned to specify and use only those lugs meeting the requirements of current UL standards.

9.5.5 Electrical and mechanical operating requirements

Electrically, the connectors must carry the current without exceeding the temperature rise of the conductors being joined. Joint resistance that is not appreciably greater than that of an equal length of conductor being joined is recommended to assure continuous and satisfactory operation of the joint. In addition, the connector must be able to withstand momentary overloads or short-circuit currents to the same degree as the conductor itself. Mechanically, a connector must be able to withstand the effects of the environment within which it is operating. When installed outdoors, it must withstand temperature extremes, wind, vibration, rain, ice, sleet, gases, chemical attack, etc. When used indoors, any vibration from rotating machinery, corrosion caused by plating or manufacturing processes, elevated temperatures from furnaces, etc., must not materially affect the performance of the joint.

9.6 Terminations

9.6.1 Purpose

A termination for an insulated power cable must provide certain basic electrical and mechanical functions. These essential requirements include the following:

a)   Electrically connect the insulated cable conductor to electric equipment, bus, or non-insulated conductor.
b)   Physically protect and support the end of the cable conductor, insulation, shielding system, and overall jacket, sheath, or armor of the cable.
c)   Effectively control electrical stresses to provide both internal and external dielectric strength to meet desired insulation levels for the cable system.

The current-carrying requirements are the controlling factors in the selection of the proper type and size of the connector or lug to be used. Variations in these components are related to the base material used for the conductor within the cable, the type of termination used, and the requirements of the electrical system.

The physical protection offered by the termination will vary considerably, depending on the requirements of the cable system, the environment, and the type of termination used. The termination must provide an insulating cover at the cable end to protect the cable components (conductor, insulation, and shielding system) from damage by any contaminants that may be present, including gases, moisture, and weathering.

Shielded medium-voltage cables are subject to unusual electrical stresses where the cable shield system is ended just short of the point of termination. The creepage distance that must be provided between the end of the cable shield, which is at ground potential, and the cable conductor, which is at line potential, will vary with the magnitude of the voltage, the type of terminating device used, and, to some degree, the kind of cable used. The net result is the introduction of both radial and longitudinal voltage gradients that impose dielectric stress of varying magnitude at the end of the cable. The termination provides a means of reducing and controlling these stresses within the working limits of the cable insulation and the materials used in the terminating device.

9.6.2 Definitions for cable terminations

The definitions for cable terminations are contained in IEEE Std 48™-2009.

A Class 1 medium-voltage cable termination, or more simply, a Class 1 termination, provides the following:

a)   Some form of electric stress control for the cable insulation shield termination

b)   Complete external leakage insulation between the medium-voltage conductor(s) and ground

c)   A seal to prevent the entrance of the external environment into the cable and to maintain the pressure, if any, within the cable system

This classification encompasses what was formerly referred to as a pothead.

A Class 2 termination provides only items a) and b): some form of electrical stress control for the cable insulation shield termination, and complete external leakage insulation, but no seal against external elements. Terminations within this classification would be stress cones with rain shields or special outdoor insulation added to give complete leakage insulation, and the newer slip-on terminations for cables having extruded insulation that do not provide a seal as in Class 1.

A Class 3 termination provides only item a): some form of electrical stress control for the cable insulation shield termination. This class of termination is used primarily indoors. Typically, this would include hand-wrapped stress cones (tapes or pennants) and the slip-on stress cones.

9.6.3 Cable terminations

The requirements imposed by the installation location dictate the termination design class. The least critical is an indoor installation within a building or inside a sealed protective housing. Here the termination is subjected to a minimum exposure to the elements (e.g., sunlight, moisture, and contamination). IEEE Std 48™-2009 refers to what is now called a Class 3 termination as an indoor termination.

Outdoor installations expose the termination to a broad range of elements and require that features be included in its construction to withstand this exposure. The present Class 1 termination defined in IEEE Std 48™-2009 was previously called an outdoor termination. In some areas, the air can be expected to carry a significant amount of gaseous contaminants and liquid or solid particles that may be conducting, either alone or in the presence of, moisture. These environments impose an even greater demand on the termination to protect the cable end, prevent damaging contaminants from entering the cable, and for the termination itself to withstand exposure to the contaminants. The termination may be required to perform its intended function while partially or fully immersed in a liquid or gaseous dielectric. These exposures impose upon the termination the necessity of complete compatibility between the liquids and exposed parts of the termination, including any gasket sealing materials. Cork gaskets have been used in the past, but the newer materials such as tetrafluoroethylene (TFE) and silicone provide superior gasketing characteristics. The gaseous dielectrics may be nitrogen or any of the electronegative gases, such as sulfur hexafluoride, that are used to fill electrical equipment.

9.6.3.1 Non-shielded cable

Cables have a copper or aluminum conductor with thermosetting or thermoplastic insulation and no shield. Terminations for these cables generally consist of a lug and may be taped. The lug is fastened to the cable by one of the methods described in 9.5, and tape is applied over the lower portion of the barrel of the lug and down onto the cable insulation. Tapes used for this purpose are selected on the basis of compatibility with the cable insulation and suitability for application in the environmental exposure anticipated.

9.6.3.2 Shielded cable

Cables rated over 2000 V have either a copper or aluminum conductor with an extruded solid dielectric insulation, such as ethylene propylene rubber (EPR) or cross-linked polyethylene (XLPE), or a laminated insulating system such as oil-impregnated paper tapes or varnished cloth tapes. A shielding system must be used on solid dielectric cables rated higher than 2 kV except under certain circumstances permitted by the NEC® (see 9.1.4.4).

When terminating shielded cable, the shielding is terminated far enough back from the conductor to provide the necessary creepage distance between the conductor and the shield. This abrupt ending of the shield introduces longitudinal stress over the surface of the exposed cable insulation. The resultant combination of radial and longitudinal electric stress at the termination of the cable results in maximum

stress occurring at this point. However, these stresses can be controlled and reduced to values within the working limits of the materials used for the termination. The most common method of reducing these stresses is to gradually increase the total thickness of insulation at the termination by adding, over the insulation, a premolded rubber cone or insulating tapes to form a cone. The cable shielding is carried up the cone surface and terminated at a point approximately 1/8-in behind the largest diameter of the cone. A typical tape construction is illustrated in Figure 33. This form is commonly referred to as a stress cone or geometric stress cone. This function can also be accomplished by using a high dielectric constant material, as compared to that of the cable insulation, either in tape form or premolded tube, applied over the insulation in this area. This method results in a low stress profile and is referred to as capacitive stress control.

It is advisable to consult individual manufacturers of cable, terminating, and splicing materials for their recommendations on terminating and splicing shielded cables.

9.6.3.3 Termination classes

A Class 1 termination is designed to handle the electrical functions as defined in 9.6.2. A Class 1 termination is used in areas that may have exposure to moisture or contaminants, or both. As pointed out in 9.6.3, the least severe requirements are those for a completely weather-protected area within a building or in a sealed protective housing. In this case, a track-resistant insulation, such as a silicone rubber tape or tube, would be used to provide the external leakage insulation function. The track-resistant surface would not necessarily need the skirts (fins or rain shields). The design of the termination to provide stress control and cable conductor seal can be the same for a weather protected, low contamination area as for a high contamination area. When a Class 1 termination is installed outdoors, the design of the termination will vary according to the external leakage insulation function that will be in the form of silicone rubber, EPDM rubber, or porcelain insulation with rain shields. Of these forms, porcelain has the better resistance to long-term exposure in highly contaminated areas and to electrical stress with arc tracking. Because of these features, they are usually chosen for coastal areas where the atmosphere is salty. The choice in other weather-exposed areas is usually based on such factors as ease of installation, time of installation, overall long-term corrosion-resistance of components, device cost, and past history. Typical Class 1 terminations are shown in Figure 34 and Figure 35.
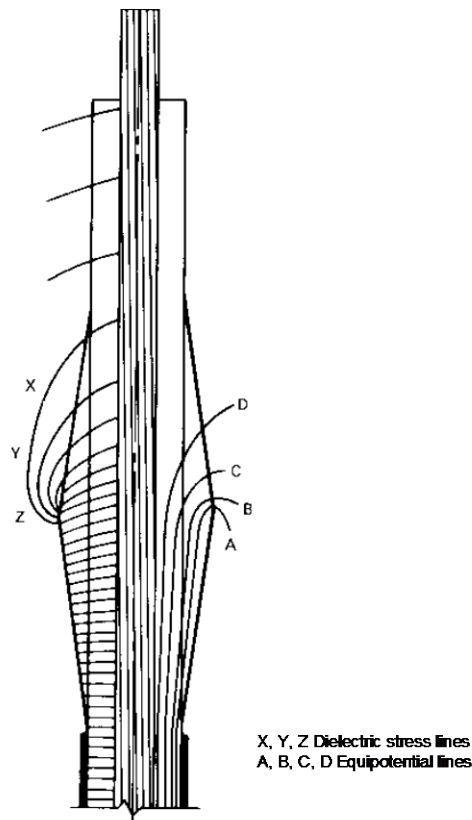
Figure 33 —Stress cone

A Class 2 termination is different from a Class 1 termination only in that it does not seal the cable end to prevent entrance of the external environment into the cable or maintain the pressure, if any, within the cable. Therefore, a Class 2 termination should not be used where moisture can enter into the cable. For a non-pressurized cable, typical of most industrial power cable systems using solid dielectric insulation, this seal is usually very easy to make. In the case of a poured porcelain terminator (commonly known as a pothead), the seal is normally built into the device. For a tape or slip-on terminator, the seal against external elements can be obtained by using tape (usually silicone rubber) to seal the conductor between the insulation and connector, assuming that the connector itself has a closed end.
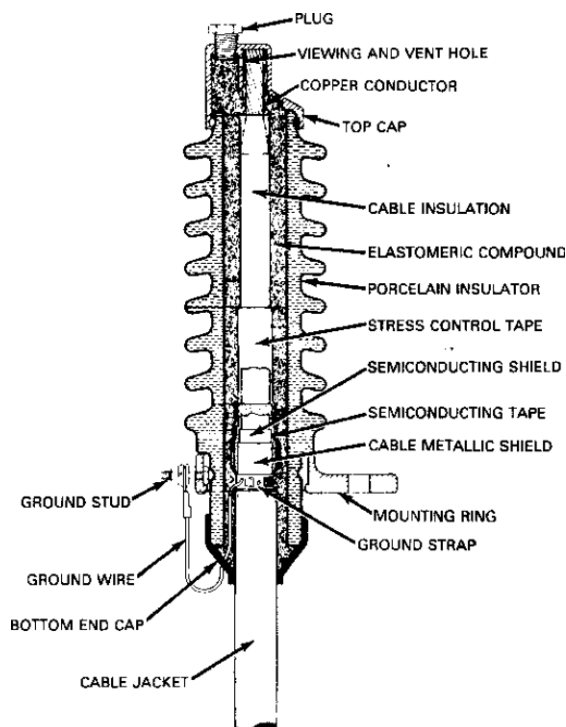
Figure 34 —Typical Class 1 porcelain terminator (for solid dielectric cables)

The Class 3 termination only provides some form of stress control. Formerly known as an indoor termination, it is recommended for use only in weather-protected areas. Before selecting a Class 3 termination, consideration should be given to the fact that, while it is not directly exposed to the elements, there is no guarantee of the complete absence of some moisture or contamination. As a result, the lack of external leakage insulation between the medium-voltage conductor(s) and ground (or track resistant material) and the seal to prevent the moisture from entering the cable can result in shortened life of the termination. In general, this practice should be avoided. A typical Class 3 termination is shown in Figure 36.

9.6.3.4 Other termination design considerations

Termination methods and devices are available in ratings of 5 kV and above for either single-conductor or three-conductor installations and for indoor, outdoor, or liquid-immersed applications. Mounting variations include bracket, plate, flanged, and free hanging types.

Both cable construction and the application should be considered in the selection of a termination method or device. Voltage rating, desired basic impulse insulation level (BIL), conductor size, and current requirements are also considerations in the selection of the termination device or method. Cable construction is the controlling factor in the selection of the proper entrance sealing method and the stress-relief materials or filling compound.
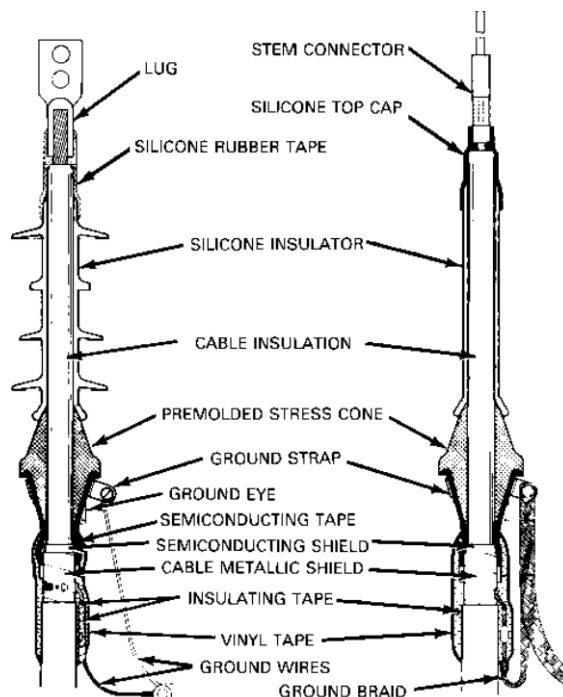
Figure 35 —Typical Class 1 molded rubber terminators (for solid dielectric cables)

Application, in turn, is the prime consideration for selecting the termination device or method, mounting requirements, and desired aerial connectors. Cable systems may be categorized into two general groups: non-pressurized and pressurized. Most power cable distribution systems are non-pressurized and utilize solid dielectric insulation.

9.6.3.5 Termination devices and methods

The termination hardware used on a pressurized cable system, which can also be used on a non-pressurized system, includes a hermetically sealed feature used to enclose and protect the cable end. A typical design consists of a metallic body with one or more porcelain insulators with fins (also called skirts or rain shields). The body is designed to accept a variety of optional cable entrance fittings, while the porcelain bushings, in turn, are designed to accommodate a number of cable sizes and aerial connections. These parts are assembled in the field onto the prepared cable ends, with stress cones required for shielded cables, and the assembled unit is filled with an insulating compound. Considerable skill is required for proper installation of this Class 1 termination, particularly in filling and cooling out, to avoid shrinkage and formation of voids in the fill material. Similar devices are available that incorporate high dielectric filling compounds, such as oil and thermosetting polyurethane resin, which do not require heating.

Advances in terminations for single conductor cables include units designed to reduce the required cable end preparation, installation time, and eliminate the hot-fill-with-compound step. One termination, applicable only to solid dielectric cables, is offered with or without a metal porcelain housing and requires the elastomeric materials to be applied directly to the cable end. Another termination consists of a metal porcelain housing filled with a gelatin-like substance designed to be partially displaced as the termination is installed on the cable. This latter unit may be used on any compatible non-pressurized cable.
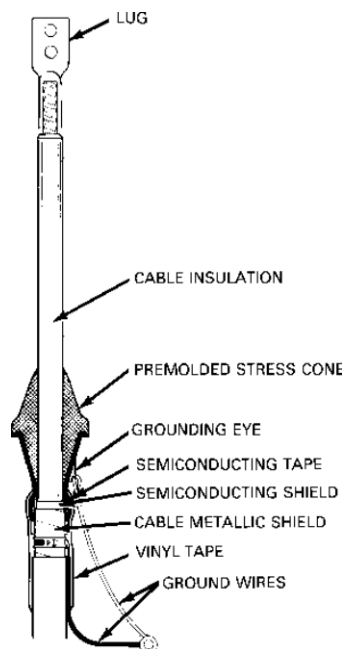
Figure 36—Typical Class 3 rubber terminator (for solid dielectric cable)

The advantages of the preassembled terminations include simplified installation procedures, reduced installation time, and consistency in the overall quality and integrity of the installed system.

Preassembled Class 1 terminations are available in ratings of 5 kV and above for most applications. The porcelain housings include flanged mounting arrangements for equipment mounting and liquid-immersed applications. Selection of preassembled termination devices is essentially the same as for poured compound devices with the exception that those units using solid elastomeric materials generally must be sized, with close tolerance, to the cable diameters to ensure proper fit.

Another category of termination devices incorporates preformed stress cones (Figure 35). The most common preformed stress cone is a two-part elastomeric assembly consisting of a semiconducting lower section formed in the shape of a stress cone and an insulating upper section. With the addition of medium-voltage insulation protection from the stress cone to the termination lug (a track-resistant silicone tape or tube, or silicone insulators or fins for weather-exposed areas) and by sealing the end of the cable, the resultant termination is a Class 2 termination, for use in areas exposed to moisture and contamination, but not required to hold pressure.

Taped terminations, although generally more time-consuming to apply, are very versatile. Generally, taped terminations are used at 15 kV and below; however, there have been instances where they were used on cables up to 69 kV. On non-shielded cables, the termination is made with only a lug and a seal, usually tape. Termination of shielded cables requires the use of a stress cone and cover tapes in addition to the lug. The size and location of the stress cone is controlled primarily by the operating voltage and whether the termination is exposed or protected from the weather.

A creepage distance of 1 in/kV of nominal system voltage is commonly used for protected areas, and a 2 in to 3 in distance allowed for exposed areas. Additional creepage distance may be gained by using a non-wetting insulation, fins, skirts, or rain hoods between the stress cone and conductor lug. For weather-exposed areas, this insulation is usually a track-resistant material, such as silicone rubber or porcelain.

Insulating tapes for the stress cone are selected to be compatible with the cable insulation, and tinned copper braid and semiconducting tape are used as conducting materials for the cone. A solid copper strap or solder-blocked braid should be used for the ground connection to prevent water wicking along the braid.

Some of the newer terminations do not require a stress cone. They utilize a stress-relief or grading tape or tube. The stress-relief or grading tape or tube is then covered with another tape or a heat shrinkable tube for protection against the environment. The exterior tape or tube may also provide a track-resistant surface for greater protection in contaminated atmospheres.

9.6.4 Jacketed and armored cable connectors

Outer coverings for these cables may be nonmetallic, such as neoprene, polyethylene, or polyvinyl chloride, or metallic, such as lead, aluminum, or galvanized steel, or both, depending upon the installation environment. The latter two metallic coverings are generally furnished in an aluminum or galvanized steel tape helically applied and interlocked over the cable core or a continuously welded and corrugated aluminum sheath. The terminations available for use with these cables provide a means of securing the outer covering and may include conductor terminations. The techniques for applying them vary with the cable construction, voltage rating, and the requirements for the installation.

The outer covering of multi-conductor cables must be secured at the point of termination using cable connectors approved both for the cable and the installation conditions.

Type MC metal-clad cables with a continuously welded and corrugated sheath or an interlocking tape armor require, in addition to cable terminators, an arrangement to secure and ground the armor. Fittings available for this purpose are generally referred to as armored cable connectors. These armored cable connectors provide mechanical termination and electrically ground the armor. This is particularly important on the continuous corrugated aluminum sheath because the sheath is the grounding conductor. In addition, the connector may provide a watertight seal for the cable entrance to a box, compartment, pothead, or other piece of electrical equipment. These connectors are sized to fit the cable armor and are designed for use on the cable alone, with brackets or with locking nuts or adaptors for application to other pieces of equipment.

9.6.5 Separable insulated connectors

These are two-part devices used in conjunction with medium-voltage electrical apparatus. A bushing assembly is attached to the medium-voltage apparatus (transformer, switch, fusing device, etc.), and a molded plug-in connector is used to terminate the insulated cable and connect the cable system to the bushing. The dead front feature is obtained by fully shielding the plug-in connector assembly.

Two types of separable insulated connectors are available: load break and deadbreak. Both utilize a molded construction design for use on solid dielectric insulated cables (rubber, cross-linked polyethylene, etc.) and are suitable for submersible applications. The connector section of the device has an elbow (90°) configuration to facilitate installation, improve separation, and save space.

9.6.5.1 Loadbreak and deadbreak types

Separable connectors are available as either a load break type or a deadbreak type, depending on the current rating. Connectors with a continuous current rating of 200 A are available in both loadbreak and deadbreak types. While one manufacturer has developed a loadbreak type connector rated 600 A, only deadbreak types rated 600 A are defined in IEEE Std 386™-2006, and only deadbreak types rated 600A are available from multiple manufacturers.

Loadbreak type connectors are differentiated from deadbreak types by their ability to be connected or disconnected while the cable is energized, whereas cables with deadbreak connectors must be deenergized before the connector is connected or separated. Loadbreak types can be used for a variety of loads; however, they are not designed for connecting capacitors and should never be used to energize or de-energize capacitors. Other interrupting devices with adequate ratings for capacitive load should be used to

de-energize capacitors and the circuit tested for proof of de-energization before loadbreak type connectors are operated.

While loadbreak types have a fault-closure current rating, the required testing is for one test on a sample, and repetitive fault closures are not evaluated. Fault closure ratings do not permit the use of loadbreak separable connectors for the practice of "fault chasing" where a connection is made onto a circuit that may still be short-circuited in an attempt to locate the fault. In fact, closure on faults can cause incremental damage and/or changes in the connector characteristics; both the elbow and its mating bushing should be replaced if exposed to a fault closure event. Re-use of a connector following a fault closure can result in the failure of the connector.

Operation and maintenance of separable insulated connectors requires proper personal protective equipment, specialized tools, and extensive training. IEEE Std 1215™ should be consulted for information concerning the operation and maintenance of separable insulated connectors.

9.6.5.2 Separable connector ratings

Separable connectors are designed primarily for use on solidly grounded medium-voltage systems. Voltage ratings and characteristics are defined by IEEE Std 386™ for maximum voltage-to-ground ratings ranging from 8.3 kV to 21.1 kV and maximum phase-to-phase voltages of 36.6 kV.

Separable connectors may be either single rated or dual-rated (see Table 29). Single rated connectors are distinguished by a single number in the voltage rating. This is the maximum voltage between the primary conductor and ground as well as the maximum recovery voltage that can appear across the contacts of a loadbreak type. For deadbreak and loadbreak types alike, single marked connectors can be applied on circuits where the voltage does not exceed the maximum line-to-ground voltage rating of the connector. But since the recovery voltage across the contacts of a loadbreak type cannot exceed this rating either, single rated loadbreak connectors are limited to single phase connections where the load is connected between phase and ground. Only loadbreak connectors can be dual-rated. Dual ratings are distinguished by two numbers separated by a slash, as in 8.3 kV/14.4 kV. The first number indicates the maximum voltage between the primary conductor and ground, while the second higher number indicates the maximum recovery voltage that can appear across the contacts. Dual-rated loadbreak connectors are suitable for use on three-phase loads where the phase-to-ground voltage does not exceed the first lower number of the dual rating and the phase-to-phase voltage does not exceed the second higher number of the dual rating. Since the insulation of the connector is rated only with respect to ground, these connectors are intended for use on solidly grounded systems. Their use is possible on high resistance grounded or ungrounded systems. The manufacturer should be consulted for assistance in selecting the proper voltage rating for such applications.
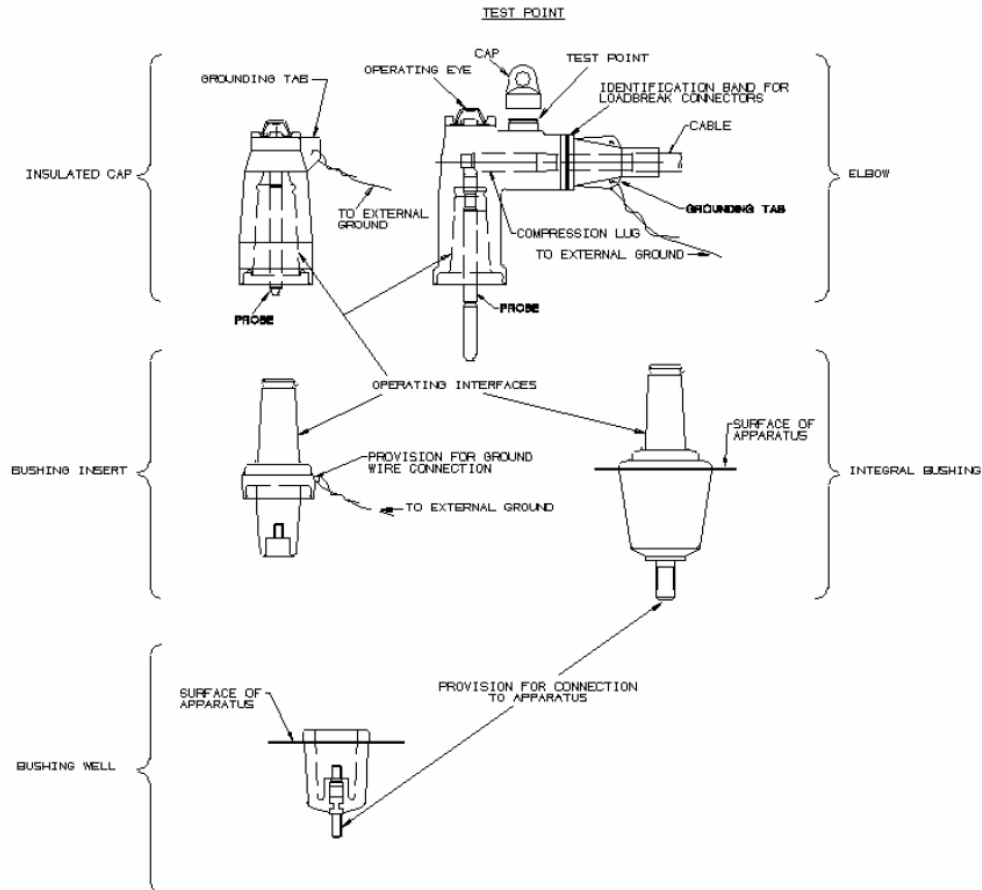
Source: IEEE Std 386™-2006

Figure 37 —Typical components of a 200 A separable insulated connector system

Separable connectors are available in continuous current ratings of either 200 A or 600 A. Loadbreak types have no overload capability. Deadbreak types can have four-hour overload capabilities that may exceed the continuous current rating by 50% or more. Manufacturer's literature should be referred to for determining actual ratings. Should there be any question regarding the overload rating of a connector, the manufacturer should be consulted.

Separable connectors have short-circuit current ratings at durations of both 170 ms (approximately 10 cycles on 60 Hz systems) and 3 s. Determination of maximum short-circuit currents and coordination of protective device ratings and settings should be used to ensure proper application of the connector for through-fault currents that may occur.

Table 29 — Voltage ratings for separable connectors

Maximum voltage rating (kV rms)[a]	Withstand voltages			
	BIL and full wave (kv crest)	AC 60 Hz for 1 min (kV rms)	DC for 15 min (kV)	Partial discharge minimum extinction voltage (kV rms)[b]
8.3[c]	95	34	53	11
8.3/14.4[d]	95	34	53	11
15.2[c]	125	40	78	19
15.2/26.3[d]	125	40	78	19
21.1[c]	150	50	103	26
21.1/36.6[d]	150	50	103	26

Source: IEEE Std 386™-2006
[a] The highest steady-state voltage across the open contacts that a loadbreak connector is rated to switch is the maximum phase-to-ground rms voltage for phase-to-ground rated devices or the maximum phase-to-phase rms voltage for phase-to-ground/phase-to-phase rated devices.
[b] Based on a sensitivity of 3 pC.
[c] Phase-to-ground.
[d] Phase-to-ground/phase-to-phase.

Table 30 — Separable connector current ratings

Connector type	Continuous current rating (A rms[a])	Switching current rating (A rms)	Overload current[a, b, c] 4 h rating (A rms)	Fault-closure current rating[d]			Short-time current rating		
				A rms, sym	Duration (s)	Min x/r	A rms, sym	Duration (s)	Min x/r
Loadbreak	200	200	--	10 000	0.17	6	10 000	0.17	6
							3 500	3.00	6
Deadbreak	200	--	300	--	--	--	10 000	0.17	6
							3 500	3.00	6
Deadbreak	600	--	900	--	--	--	25 000	0.17	20
							10 000	3.00	20

Source: IEEE Std 386™-2006
[a] In general, the overload capability of a connector exceeds its continuous current rating. Overload capability varies with environment, cable sizes, etc. The connector manufacturer's recommendations should be obtained for the particular combination involved.
[b] Consult the manufacturer for ratings that exceed those listed in the table.
[c] One overload cycle during a 24 h period.

9.6.5.3 Separable connector accessories

Accessories available for use with separable connectors include the following:

— Multiway junctions and feed-thrus

— Insulated parking bushings

— Deadfront arresters

— Elbow arresters

— Parking bushing arresters

— Bushing insert arresters

— Protective caps

— Bushing shipping caps

— Grounding elbow

— Grounding bushing

Refer to IEEE Std 1215™ for further details on these accessories.

9.6.6 Performance requirements

Design test criteria have been established for terminations in IEEE Std 48™-2009, which specifies the short-time ac 60 Hz and impulse-withstand requirements. Also listed in this design standard are maximum dc field proof test voltages. Individual terminations may safely withstand higher test voltages, and the manufacturer should be contacted for such information. All devices employed to terminate insulated power cables should meet these basic requirements. Additional performance requirements may include thermal load cycle capabilities of the current-carrying components, the environmental performance of completed units, and the long-term overvoltage-withstand capabilities of the device.

9.7 Splicing devices and techniques

Splicing devices are subjected to a somewhat different set of voltage gradients and dielectric stress from that of a cable termination. In a splice, as in the cable itself, the greatest stresses are around the conductor and connector area and at the end of the shield. Splicing design must recognize this fundamental consideration and provide the means to control these stresses to values within the working limits of the materials used to make up the splice.

In addition, on shielded cables, the splice is in the direct line of the cable system and must be capable of handling any ground currents or fault currents that may pass through the cable shielding.

The connectors used to join the cable conductors together must be electrically capable of carrying the full-rated load, emergency overload, and fault currents without overheating, as well as being mechanically strong enough to prevent accidental conductor pullout or separation.

Finally, the splice housing or protective cover must provide adequate protection to the splice, giving full consideration to the nature of the application and its environmental exposure.

a) *600 V and below.* An insulating tape is applied over the conductor connection to electrically and physically seal the joint. The same taping technique is employed in the higher voltages, but with more refinement to cable end preparation and tape applications.

Insulated connectors are used where several relatively large cables must be joined together. These terminators, called moles or crabs, are, fundamentally, insulated buses with a provision for making a number of tap connections that can be very easily taped or covered with an insulating sleeve. Connectors of this type enable a completely insulated multiple connection to be made without the skilled labor normally required for careful crotch taping or the expense of special junction boxes. One widely used connector is a pre-insulated multiple joint in which the cable connections are made mechanically by compression cones and clamping nuts. Another type is a more compact pre-insulated multiple joint in which the cable connections are made by standard compression tooling that indents the conductor to the tubular cable sockets. Also available are tap connectors that accommodate a range of conductor sizes and have an independent insulating cover. After the connection is made, the cover is snapped closed to insulate the joint.

Insulated connectors lend themselves particularly well to underground services and industrial wiring where a large number of multiple connections must be made.

b) *Over 600 V.* Splicing of non-shielded cables up to 8 kV consists of assembling a connector, usually soldered or pressed onto the cable conductors, and applying insulating tapes to build up the insulation wall to a thickness of 1.5 to 2 times that of the original insulation on the cable. Care must be exercised in applying the connector and insulating tapes to the cables; but it is not as critical with non-shielded cables as with shielded cables.

Aluminum conductor cables require a moistureproof joint to prevent entry of moisture into the stranding of the aluminum conductors.

Splices on solid dielectric cables are made with uncured tapes that will fuse together after application and provide a waterproof assembly. It is necessary, however, to use a moistureproof adhesive between the cable insulation and the first layer of insulating tapes. Additional protection may be obtained through the use of a moistureproof cover over the insulated splice. This cover may consist of additional moistureproof tapes and paint or a sealed weatherproof housing of some form.

9.7.1 Taped splices

Taped splices (see Figure 38) for shielded cables have been used quite successfully for many years. Basic considerations are essentially the same as for non-shielded cables. Insulating tapes are selected not only on the basis of dielectric properties but also for compatibility with the cable insulation. The characteristics of the insulating tapes must also be suitable for the application of the splice. This latter consideration should include such details as providing a moisture seal for splices subjected to water immersion or direct burial, thermal stability of tapes for splices subjected to elevated ambient and operating temperatures, and ease of handling for applications of tapes on wye or tee splices.

Connector surfaces should be smooth and free from any sharp protrusions or edges. The connector ends are tapered, and indentations or distortion caused by pressing tools are filled and shaped to provide a round, smooth surface. Semiconducting tapes are recommended for covering the connector and the exposed conductor stranding to provide a uniform surface over which insulating tapes can be applied. Cables with a solid dielectric insulation are tapered, and those with a tape insulation are stepped to provide a gradual transition between the conductor/connector diameter and the cable insulation diameter prior to application of the insulating tapes. This is done to control the voltage gradients and resultant voltage stress to values within the working limits of the insulating materials. The splice should not be overinsulated to provide additional protection since this could restrict heat dissipation at the splice area and risk splice failure.

A tinned or coated copper braid is used to continue the shielding function over the splice area. Grounding straps are applied to at least one end of the splice for grounding purposes, and a heavy braid jumper is applied across the splice to carry available ground fault current. Refer to 9.8.1 for single-point grounding to reduce sheath losses.

Final cover tapes or weather barriers are applied over the splice to seal it against moisture entry. A splice on a cable with a lead sheath is generally housed in a lead sleeve that is solder wiped to the lead cable sheath at each end of the splice. These lead sleeves are filled with compound in much the same way as potheads.

Hand-taped splices may be made between lengths of dissimilar cables if proper precautions are taken to ensure the integrity of the insulating system of each cable and the tapes used are compatible with both cables. One example of this would be a splice between a rubber insulated cable and an oil-impregnated paper insulated cable. Such a splice must have an oil barrier to prevent the oil impregnate in the paper cable from coming in contact with the insulation on the rubber cable. In addition, the assembled splice should be made completely moistureproof. This requirement is usually accomplished by housing the splice in a lead sleeve with wiped joints at both ends. A close-fitting lead nipple is placed on the rubber cable and sealed to the jacket of the cable with tape or epoxy. The solder wipe is made to this lead sleeve.

Three-way wye and tee splices and the several other special hand-taped splices that can be made all require special design considerations. In addition, a high degree of skill on the part of the installer is a prime requirement for proper installation and service reliability.
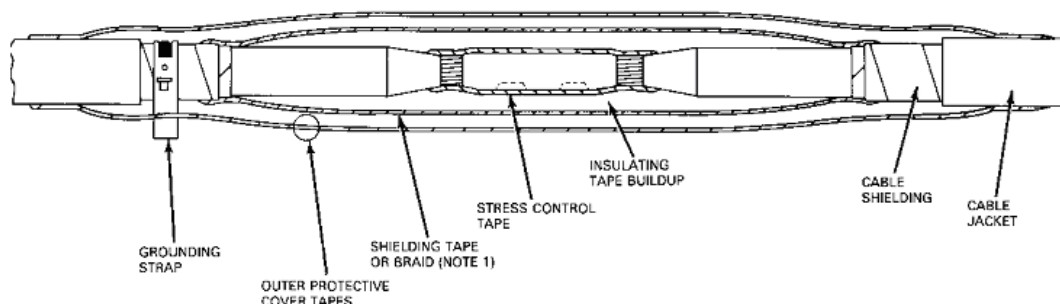
NOTE 1—Heavy braid jumper or perforated strip should be used across splice to carry possible ground-fault current. Stress-control tape should cover strands completely, lapping slightly onto insulation taper.

NOTE 2—Consult individual cable supplier for recommended installation procedures and materials.

Figure 38 — Typical taped splice in shielded cable

9.7.2 Preassembled splices

Similar to the preassembled terminators, there are several variations of factory-made splices. The most basic is an elastomeric unit consisting of a molded housing sized to fit the cables involved, a connector for joining the conductors, and tape seals for sealing the ends of the molded housing to the cable jacket. Other versions of elastomeric units include an overall protective metallic housing that completely encloses the splice. These preassembled elastomeric splices are available in two- and three-way tees, and multiple configurations for applications up to 35 kV. They can be used on most cables having an extruded solid dielectric insulation.

The preassembled splice provides a moistureproof seal to the cable jacket and is suitable for submersible, direct burial, and other applications where the splice housing must provide protection for the splice to the same degree that the cable jacket provides protection to the cable insulation and shielding system. An advantage of these preassembled splices is the reduction in time required to complete the splice after cable end preparation. However, the solid elastomeric materials used for the splice are required to be sized, with close tolerance, to the cable diameters to ensure a proper fit.

9.8 Grounding of cable systems

For safety and reliable operation, the shields and metallic sheaths of power cables must be grounded. Without grounding, shields would operate at a potential considerably above ground. Thus, they would be hazardous to touch and would cause rapid degradation of the jacket or other material intervening between shield and ground. This is caused by the capacitive charging current of the cable insulation that is on the order of 3.3 mA/m (1 mA/ft) of conductor length. This current normally flows at power frequency between the conductor and the earth electrode of the cable, normally the shield. In addition, the shield or metallic sheath provides a fault return path in the event of insulation failure, permitting rapid operation of the protection devices.

The grounding conductor and its attachment to the shield or metallic sheath, normally at a termination or splice, should have an ampacity no less than that of the shield. In the case of a lead sheath, the ampacity of

the grounding conductor should be adequate to carry the available fault current without overheating until it is interrupted. Attachment to the shield or sheath is frequently done with solder, which has a low melting point; thus an adequate area of attachment is required.

There is much disagreement as to whether the cable shield should be grounded at both ends or at only one end. If grounded at only one end, any possible fault current must traverse the length from the fault to the grounded end, imposing high current on the usually very light shield conductor. Such a current could readily damage or destroy the shield and require replacement of the entire cable rather than only the faulted section. With both ends grounded, the fault current would divide and flow to both ends, reducing the duty on the shield with consequently less chance of damage. There are modifications to both systems. In one, single-ended grounding may be attained by insulating the shields at each splice or sectionalizing point and grounding only the source end of each section. This limits possible shield damage to only the faulted section. Multiple grounding, rather than just grounding at both ends, is simply the grounding of the cable shield or sheath at all access points, such as manholes or pull boxes. This also limits possible shield damage to only the faulted section.

9.8.1 Sheath losses

Currents are induced in the multigrounded shields and sheaths of cables by the current flowing in the power conductor. These currents increase with the separation of the power conductors and increase with decreasing shield or sheath resistance. This sheath current is negligible with three conductor cables, but with single-conductor cables separated in direct burial or separate ducts, it can be appreciable. For example, with three single-conductor 500 kcmil cables laid parallel on 8-in centers with twenty spiral No. 16 AWG copper shield wires, the ampacity is reduced approximately 20% by this shield current. With single-conductor, lead-sheathed cables in separate ducts, this current is important enough that single-end grounding is mandatory. As an alternate, the shields are insulated at each splice (at approximately 500 ft intervals) and crossbonded to provide sheath transposition. This neutralizes the sheath currents, but still provides double-ended grounding. Of course, these sheaths and the bonding jumpers must be insulated; their voltage differential from ground may be in the 30 V to 50 V range. For details on calculating sheath losses in cable systems, consult the National Electrical Safety Code® (NESC®) (Accredited Standard Committee C2-2007).

Difficulties may arise from current attempting to flow via the cable shield, unrelated to cable-insulation failures. To prevent this, all points served by a multiple-grounded shielded cable need to be interconnected with an ample grounding system. The insulation between shield sections at splices of single-end grounded shield systems should have sufficient dielectric strength to withstand possible abnormal voltages as well. This system requires interconnecting grounding conductors of suitably low impedance that lightning, fault, and stray currents will follow this path rather than the cable shield. Cable shield ground connections should be made to this system, which should also be connected to the grounded element of the source supplying the energy to the cable. Duct runs, or direct burial routes, generally include a heavy grounding conductor to ensure such interconnection. For further details, refer to IEEE Std 141™-1993 (*IEEE Red Book™*), Chapter 7, as well as to IEEE Std 142™-2007 (*IEEE Green Book™*) and the NESC®.

9.9 Protection from transient overvoltage

Cables rated up to 35 kV that are used in power distribution systems have insulation strengths well above that of other electrical equipment of similar voltage ratings. This is to compensate for installation handling and possibly a deterioration rate greater than for insulation that is exposed to less severe ambient conditions. This high insulation strength may or may not exist in splices or terminations, depending on their design and construction. Except for deteriorated points in the cable itself, the splices or terminations are most affected by overvoltages of lightning and switching transients. The terminations of cable systems not provided with surge protection may flashover due to switching transients. In this event, the cable would be

subjected to possible wave reflections of even higher levels, possibly damaging the cable insulation; however, this is a remote possibility in medium-voltage cables.

Like other electric equipment, the means employed for protection from these overvoltages is usually surge arresters. These may be for protection of associated equipment as well as the cable. Distribution or intermediate class arresters are used, applied at the junctions of open wire lines and cables, and at terminals where switches may be open. Surge arresters are not required at intermediate positions along the cable run in contrast to open wire lines.

It is recommended that surge arresters be connected between the conductor and the cable shielding system with short leads to maximize the effectiveness of the arrester. Similarly recommended is the direct connection of the shields and arrester ground wires to a substantial grounding system to prevent surge current propagation through the shield.

Fully insulated aerial cables that are messenger supported and spacer cables are subject to direct lightning strokes, and a number of such cases are on record. The incidence rate is, however, rather low, and, in most cases, no protection is provided. Where, for reliability, such incidents must be guarded against, a grounded shield wire, similar to that used for bare aerial circuits, should be installed on the poles a few feet above the cable. Grounding conductors down the pole need to be carried past the cable messenger with a lateral offset of approximately 18 in to guard against side flashes from the direct strokes. Metal bayonets, when used to support the grounded shielding wire, should also be kept no less than 18 in clear of the cables or messengers.

9.10 Testing

9.10.1 Application and utility

Testing, particularly of elastomeric and plastic (solid) insulations, is a useful method of checking the ability of a cable to withstand service conditions for a reasonable future period. Failure to pass the test will either cause breakdown of the cable during test or otherwise indicate the need for its immediate replacement.

Whether or not to routinely test cables is a decision each user has to make. The following factors should be taken into consideration:

a) If there is no alternate source for the load supplied, testing should be done when the load equipment is not in operation
b) The costs of possible service outages due to cable failures should be weighed against the cost of testing. With solid dielectric insulation, failures of cables in service may be reduced approximately 90% by dc maintenance testing
c) Personnel with adequate technical capability should be available to do the testing, make observations, and evaluate the results

Detailed procedures are provided in IEEE Std 3007.2™ [B43].

9.10.2 Alternating current versus direct current

Cable insulation can, without damage, sustain application of dc potential equal to the system basic impulse insulation level (BIL) for very long periods. In contrast, most cable insulations will sustain degradation from ac overpotential, proportional to the overvoltage, time of exposure, and the frequency of the applications. Therefore, it is desirable to utilize dc for any testing that will be repetitive. While the manufacturers use ac for the original factory test, it was a universal practice to employ dc for any subsequent testing. However, dc voltage can stress an insulation system differently than ac voltage in a way

that does not reflect the normal operating conditions. The electric field gradient imposed by dc voltage is a function of the system capacitance rather than the system impedance as in the case of ac voltage testing. This becomes an issue when conducting high-potential testing on complex insulations systems employing layered materials with different dielectric constants since the voltage gradient imposed by dc voltage could be higher than that imposed by an equivalent ac voltage. Application of a dc voltage in such situations can weaken the insulation and lead to premature failure. A comparison of four methods for field assessment of the dielectric response of medium-voltage shielded power cable can be found in IEEE Std 400™-2012.

9.10.3 Factory tests

All cable is tested by the manufacturer before shipment, normally with ac voltage for a 5 min period. Non-shielded cable is immersed in water (ground) for this test; shielded cable is tested using the shield as the ground return. Test voltages are specified by the manufacturer, by the applicable UL or ICEA specification, or by other specifications such as those published by the Association of Edison Illuminating Companies (AEIC); refer to AEIC CS8-07. In addition, a test may be made using dc voltage of two to three times the rms value used in the ac test. On cables rated over 2 kV, corona tests may also be made.

9.10.4 Field tests

As well as having no deteriorating effect on good insulation, dc high voltage is the most convenient to use for field testing since the test power sources or test sets are relatively light and portable. However, it should be recognized that correlation between dc test results and cable life expectancy has never been established.

The primary benefit of dc high voltage testing is to detect conducting particles left on the creepage surface during splicing or termination. Voltages for such testing should not be so high as to damage sound cable or component insulation but should be high enough to indicate incipient failure of unsound insulation that may fail in service before the next scheduled test.

Details on recommended practices for test voltages, intervals, and procedures are provided in IEEE Std 3007.2™ and IEEE Std 400™-2012.

9.11 Cable specification

Once the correct cable has been determined, it can be described in a cable specification. Cable specifications generally start with the conductor and progress radially through the insulation and coverings. The following is a check list that can be used in preparing a cable specification:

a)   Number of conductors in cable, and phase identification required

b)   Conductor size (AWG, kcmil) and material

c)   Insulation (rubber, polyvinyl chloride, XLPE, EPR, etc.)

d)   Voltage rating, and whether system requires 100%, 133%, or 173% insulation level

e)   Shielding system, required on cable systems rated 8 kV and above and may be required on systems rated 2001 V to 8000 V

f)   Outer finishes

g)   Installation approvals required (for use in cable tray, direct burial, messenger-supported, wet location, exposure to sunlight or oil, etc.)

h)   Applicable UL listing

i)   Test voltage and partial-discharge voltage

j)   Ground-fault-current value and time duration

k)   Cable accessories, if any, to be supplied by cable manufacturer

An alternate method of specifying cable is to furnish the ampacity of the circuit (amperes), the voltage (phase-to-phase, phase-to-ground, grounded, or ungrounded), and the frequency, along with any other pertinent system data. Also required is the installation method and the installation conditions (ambient temperature, load factor, etc.). For either method, the total number of linear feet of conductors required, the quantity desired shipped in one length, any requirement for pulling eyes, and whether it is desired to have several single-conductor cables paralleled on a reel should also be given.

Annex A

(informative)

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